MSC-03909

HABITABILITY DATA HANDBOOK

VOLUME 4

FOOD MANAGEMENT

(NASA-TM-X-68330) HABITABILITY DATA HANDBOOK. VOLUME 4: FOOD MANAGEMENT (NASA) 31 Jul. 1971 136 p

N72-72874

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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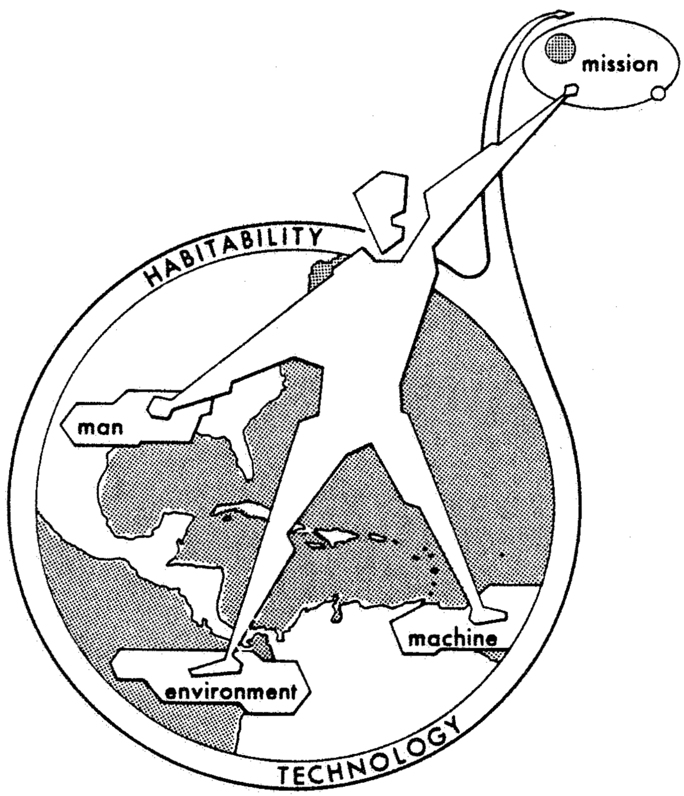


PREPARED BY

HABITABILITY TECHNOLOGY SECTION

SPACECRAFT DESIGN DIVISION

MANNED SPACECRAFT CENTER

PREFACE

The Habitability Data Handbook is a collection of data in six volumes which include requirements, typical concepts, and supporting parametric data. The handbook provides an integrated data source for use in habitability system planning and design, intersystem trade-offs, and interface definition. The following volumes comprise the Habitability Data Handbook:

Volume	Title
1	Mobility and Restraint
2	Architecture and Environment
3	Housekeeping
4	Food Management
5	Garments and Ancillary Equipment
6	Personal Hygiene

This volume provides data for food management applicable to extraterrestrial habitats and vehicles.

These data are considered preliminary and are predominantly derived from analytical and terrestrial sources and in general lack zero-g verification.

CONTENTS

CONTENTS (CONCLUDED)

2.0 WEIGHT AND VOLUME FACTORS FOR GIVEN FOOD MIX RATIOS

2.1 FOOD DEFINITIONS AND ASSUMPTIONS

Nutrition - Selection of foods for nutritional value is not considered within the scope of this handbook. However, for purposes of this handbook, nutritionally adequate food is defined as food which provides 2800 calories per day.

Dry Food - Dry foods are foods that contain less than 5 percent water, by weight. Dry foods are considered to be shelf stable and can be stored at ambient conditions.

Wet Food - Wet foods are foods that contain 5% or more water, by weight. Wet foods are classified according to storage requirements as follows: frozen, shelf stable, and perishable (refrigerated).

- Frozen Food - Contains 66 percent water by weight and can be stored at -10°F.
- Shelf Stable Food - Contains 66 percent water by weight and can be stored at ambient storage conditions.
- Perishable Food - Contains 60 percent water by weight and must be stored between 32 and 40°F.

2.2 FOOD AND WATER REQUIREMENTS

The following food and water requirements are the basis for all food weight and volume computations presented in this handbook:

- 1.5 pounds of dry (waterless) food required per man-day
- 5.5 pounds of potable water required per man-day (food content water plus drinking water).

2.3 FOOD MIX RATIOS

Food mix ratio is a means of designating the proportion of nutritionally adequate food that is dry (numerator) versus that which is wet (denominator). The dry to wet food mix ratios presented in this handbook are as follows:

Dry %	80	60	50	40	20
Wet %	20	40	50	60	80

The wet mix ratios are further broken down into percentages of frozen, shelf stable, and perishable foods.

Frozen	30%
Shelf Stable	50%
Perishable	20%

The average water content and density of each food type is expressed as a percentage of total wet weight as follows:

Food Type	Water Content (%)	Dry Food Content (%)	Average Density (lb/ft^3)
Dry	4	96	25
Frozen	66	34	50
Shelf Stable	66	34	50
Perishable	60	40	30

2.4 FOOD WEIGHT FACTORS

Food weight factors in pounds per man-day (based on 1.5 lbs of dry food required per man-day) are presented in Table 2-1. The factors have been computed for each of the food types and mix ratios presented in Paragraph 2.3, and were derived from the following equation:

Food wet weight factor = % food type x (1.5 lb ÷ 1-% water content)

The weight of food for any number of man-days may be obtained by multiplying the food weight factor by the desired number of man-days. The wet weights of food per man-day for each food mix ratio are also presented in graphic form in Figure 2-1. These curves may be extended to any number of man-days and food weight by multiplying the ordinate and abscissa by an appropriate factor, i.e., 10, 100, 1000.

2.5 FOOD VOLUME FACTORS

Food volume factors in cubic feet per man-day are presented in Table 2-2. These factors have been computed using the following formula:

Food wet volume factor = wet weight of food ÷ average density

The volume of food for any number of man-days may be obtained by multiplying the food volume factor by the desired number of man-days. The wet volumes of food per man-day for each food mix ratio are also presented in graphic form in Figure 2-2. These curves may be extended to any number of man-days and food volume by multiplying the ordinate and abscissa by an appropriate factor, i.e., 10, 100, 1000.

Table 2-1. Food Weight Factors Per Man-Day

Food Mix Ratio Dry/Wet (%)	Food Mix Portion (%)				Wet Weight of Food (lb)				Total Weight Per Mix Ratio (lb)
	Dry Food	Wet Food*			Dry Food	Wet Food*			
		Frozen	Shelf Stable	Perishable		Frozen	Shelf Stable	Perishable	
80/20	80	6	10	4	1.250	0.265	0.441	0.150	2.106
60/40	60	12	20	8	0.938	0.529	0.882	0.300	2.649
50/50	50	15	25	10	0.781	0.662	1.103	0.375	2.921
40/60	40	18	30	12	0.625	0.794	1.324	0.450	3.193
20/80	20	24	40	16	0.313	1.059	1.765	0.600	3.737

*Wet food is proportioned 30% frozen, 50% shelf stable, and 20% perishable for each food mix ratio.

Table 2-2. Food Volume Factors Per Man-Day

Food Mix Ratio Dry/Wet (%)	Food Mix Portion (%)				Wet Volume of Food (ft^3)				Total Volume Per Mix Ratio (ft^3)
	Dry Food	Wet Food*			Dry Food	Wet Food*			
		Frozen	Shelf Stable	Perishable		Frozen	Shelf Stable	Perishable	
80/20	80	6	10	4	0.0500	0.0053	0.0088	0.0050	0.0691
60/40	60	12	20	8	0.0375	0.0106	0.0176	0.0100	0.0757
50/50	50	15	25	10	0.0312	0.0132	0.0221	0.0125	0.0790
40/60	40	18	30	12	0.0250	0.0159	0.0265	0.0150	0.0824
20/80	20	24	40	16	0.0125	0.0212	0.0353	0.0200	0.0890

*Wet food is proportioned 30% frozen, 50% shelf stable, and 20% perishable for each food mix ratio.

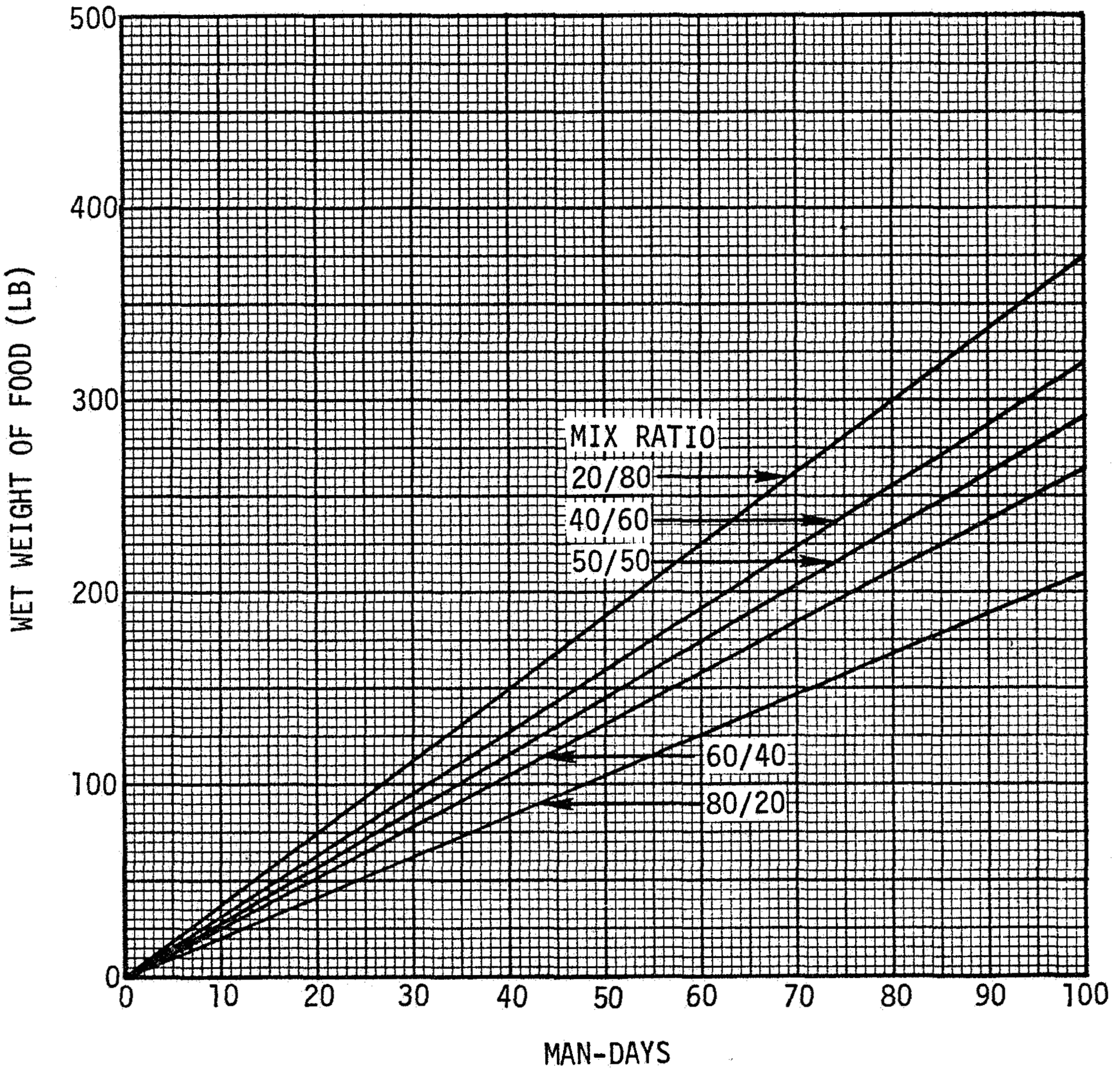


Figure 2-1. Food Weight Comparison for Various Mix Ratios

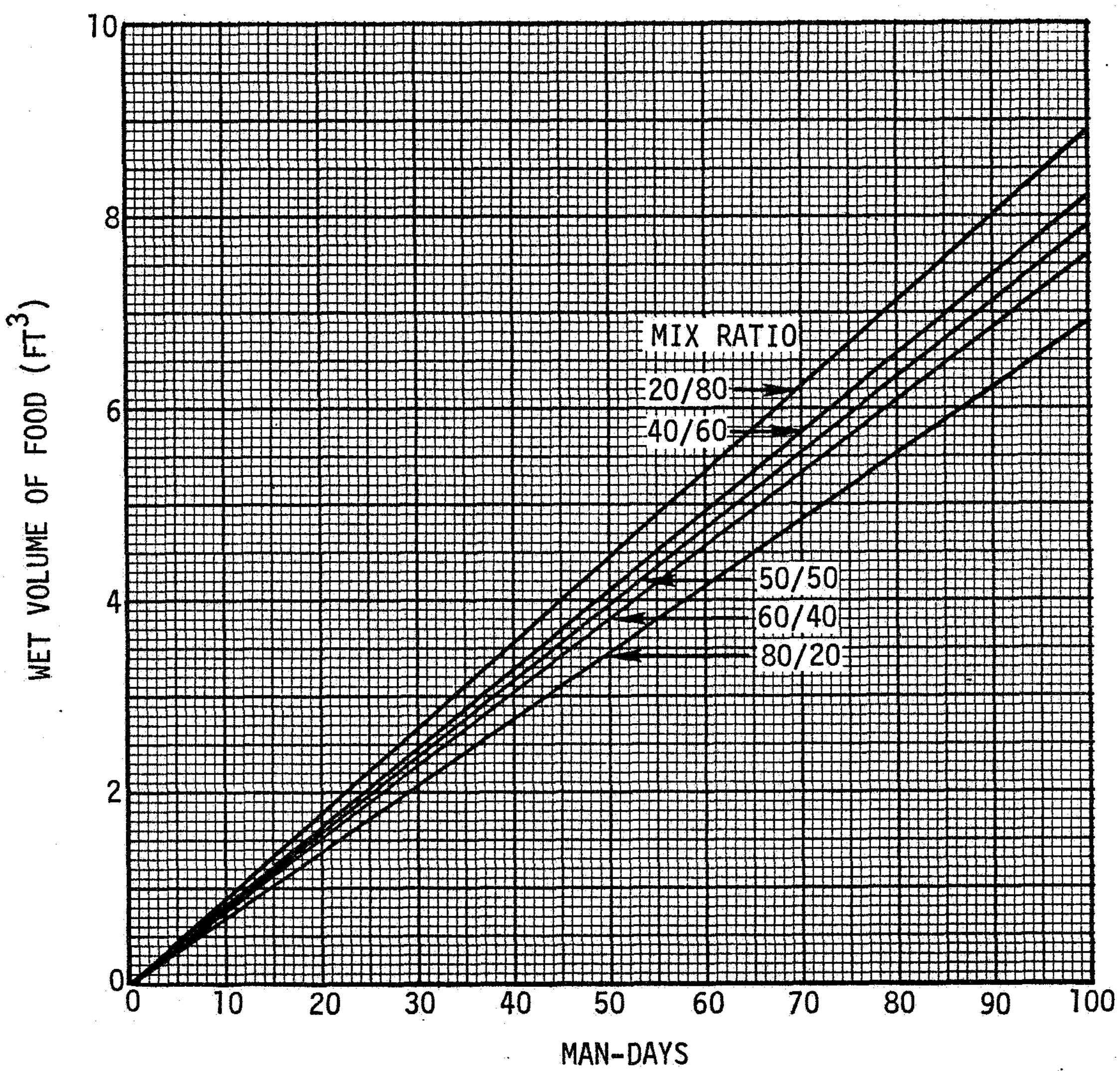


Figure 2-2. Food Volume Comparison for Various Mix Ratios

2.6 DAILY BIOLOGICAL WATER

The additional daily water required per man-day to supplement the water contained in the food diet for each food mix ratio is tabulated in Table 2-3. The total additional water required for any number of man-days can be obtained by multiplying the number of man-days by the pounds of water required per man-day for the appropriate mix ratio. The additional pounds of water required per man-day are plotted in Figure 2-3. These curves may be extended to any number of man-days and water weights by multiplying the ordinate and abscissa by an appropriate factor, i.e., 10, 100, 1000.

Table 2-3. Daily Biological Water Requirements

Food Mix Ratios (%)	Dry Weight of Food (lb)	Wet Weight of Food (lb)	Weight of Water Contained in Food (lb)	Total Water Requirements Per Man-Day (lb)	Additional Daily Water Required Per Man-Day (lb)
80/20	1.5	2.106	0.606	5.5	4.894
60/40	1.5	2.649	1.149	5.5	4.351
50/50	1.5	2.921	1.421	5.5	4.079
40/60	1.5	3.193	1.693	5.5	3.807
20/80	1.5	3.737	2.237	5.5	3.263

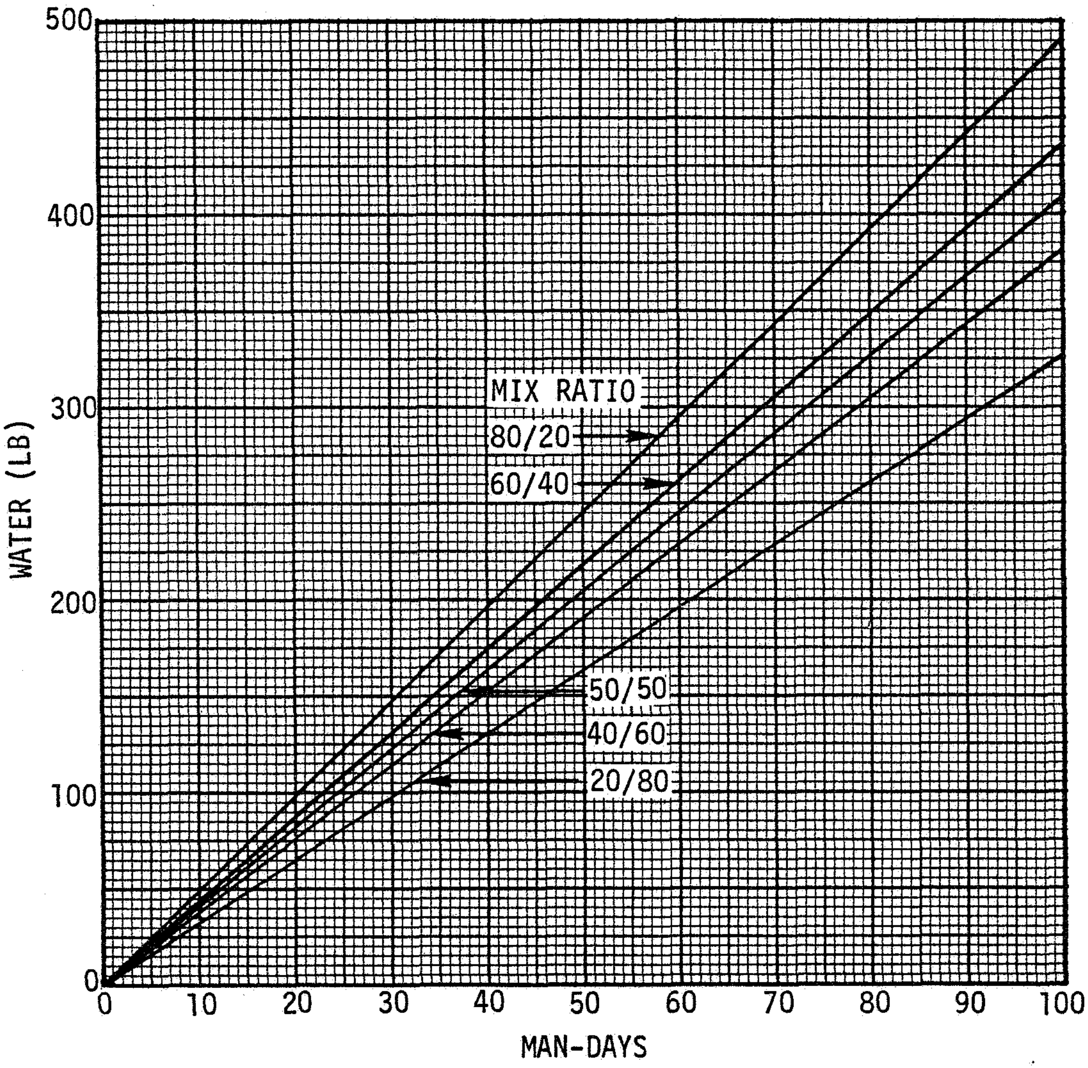


Figure 2-3. Additional Water Required to Meet 5.5 lb/Man-Day for Various Mix Ratios

3.0 FOOD PACKAGING

The two factors considered in space-oriented food packaging are the planned earth-like environment and the inclusion of familiar foods in the diet. The environment factor precludes consideration of foil laminates and pressure vessels. The addition of familiar foods necessitates use of packages which are compatible with refrigerator, freezer, and pantry (ambient) storage.

3.1 CONCEPTS

Representative packaging types for dry, frozen, shelf stable, and perishable food are as follows:

- Canned: steel and tin cans
- Box and Bag: paperboard box with a polyethylene bag liner
- Bag: polyethylene bag
- Cylindrical: rigid polyethylene container and pull-ring aluminum can

3.2 PACKAGED FOOD WEIGHT

Packaged food weight factors (ratio of package weight to wet weight of food) were derived for each package type and are presented in Table 3-1. Packaged food weights per man-day were computed for each packaging technique and are presented in Table 3-2. Packaged food weights were computed by the following method.

Packaged food weight = package weight factor x weight of food + weight of food

where:

Package weight factors are obtained from Table 3-1.

Food weights are obtained from Table 2-1.

Packaged food weight for any number of man-days can be obtained by multiplying by the desired number of man-days. Packaged food weight per man-days for each packaging method and food type are also presented in graphic form in Figures 3-1 through 3-5. These curves may be extended to any number of man-days and packaged weights by multiplying the ordinate and abscissa by an appropriate factor, i.e., 10, 100, 1000.

(Text continued on Page 3-8.)

Table 3-1. Food Package Weight Factors (Pounds Package ÷ Pounds Food)

Food and Storage Type	Canned	Box and Bag	Bag	Cylindrical
Dry (Ambient)	0.272	0.130	N/A	0.114
Frozen (Freezer)	N/A	0.082	0.015	0.014
Shelf Stable (Ambient)	0.272	0.130	N/A	0.114
Perishable (Refrigerated)	N/A	0.102	0.035	0.095

Table 3-2. Packaged Food Weight for Various Mix Ratios

Food and Package Type	Packaged Weight of Food for Various Mix Ratios (lb/man-day)				
	80/20	60/40	50/50	40/60	20/80
Dry Food					
Canned	1.590	1.193	0.993	0.795	0.398
Box and Bag	1.413	1.060	0.883	0.706	0.354
Bag	N/A	N/A	N/A	N/A	N/A
Cylindrical	1.393	1.045	0.870	0.696	0.349
Frozen Food					
Canned	N/A	N/A	N/A	N/A	N/A
Box and Bag	0.287	0.572	0.716	0.859	1.146
Bag	0.269	0.537	0.672	0.806	1.075
Cylindrical	0.269	0.536	0.671	0.805	1.074
Shelf Stable Food					
Canned	0.561	1.122	1.403	1.684	2.245
Box and Bag	0.498	0.997	1.246	1.496	1.994
Bag	N/A	N/A	N/A	N/A	N/A
Cylindrical	0.491	0.983	1.229	1.475	1.966
Perishable Food					
Canned	N/A	N/A	N/A	N/A	N/A
Box and Bag	0.165	0.331	0.413	0.496	0.661
Bag	0.155	0.311	0.388	0.466	0.621
Cylindrical	0.164	0.329	0.411	0.493	0.657

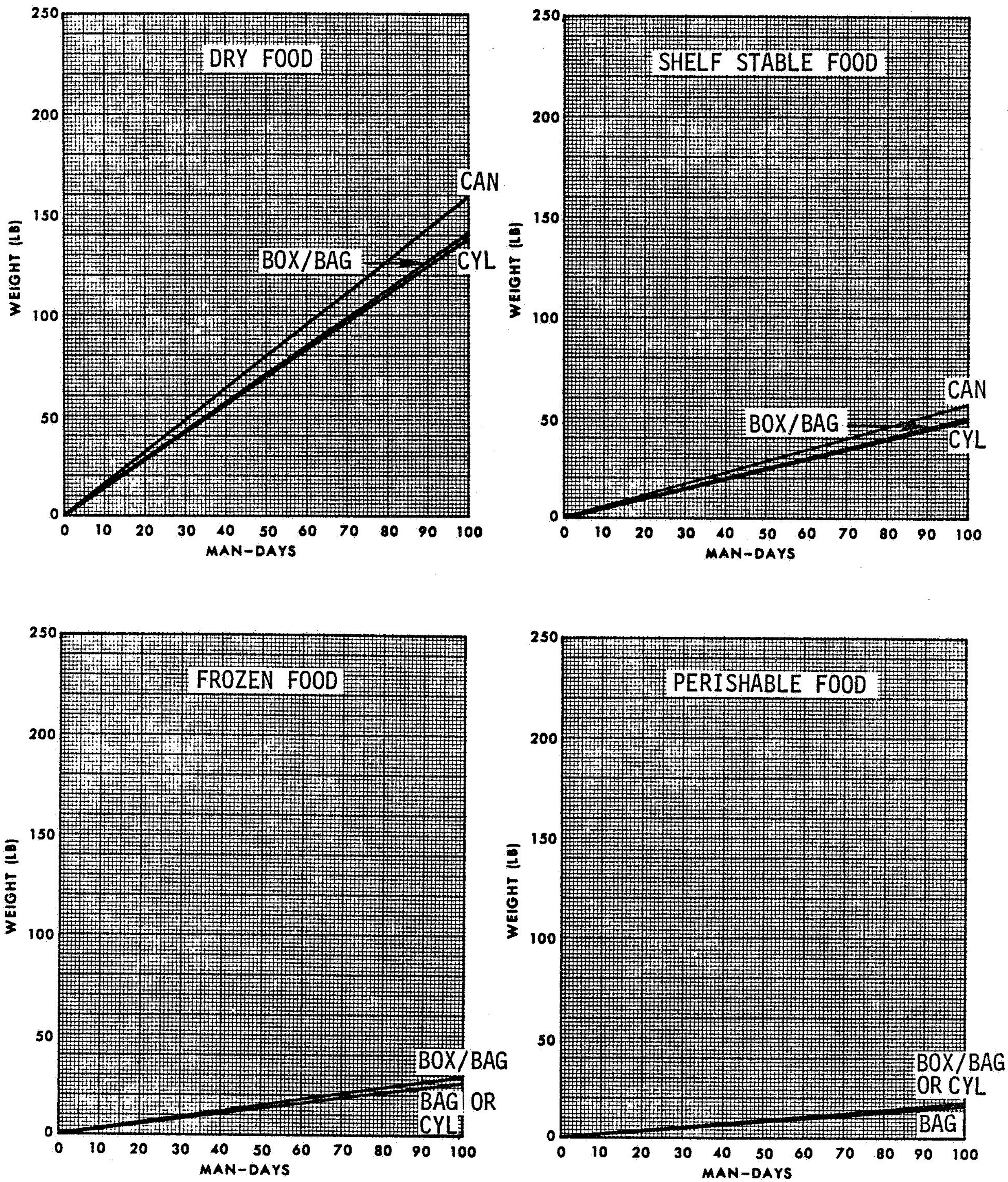


Figure 3-1. Packaged Food Weight for 80/20 Mix Ratio

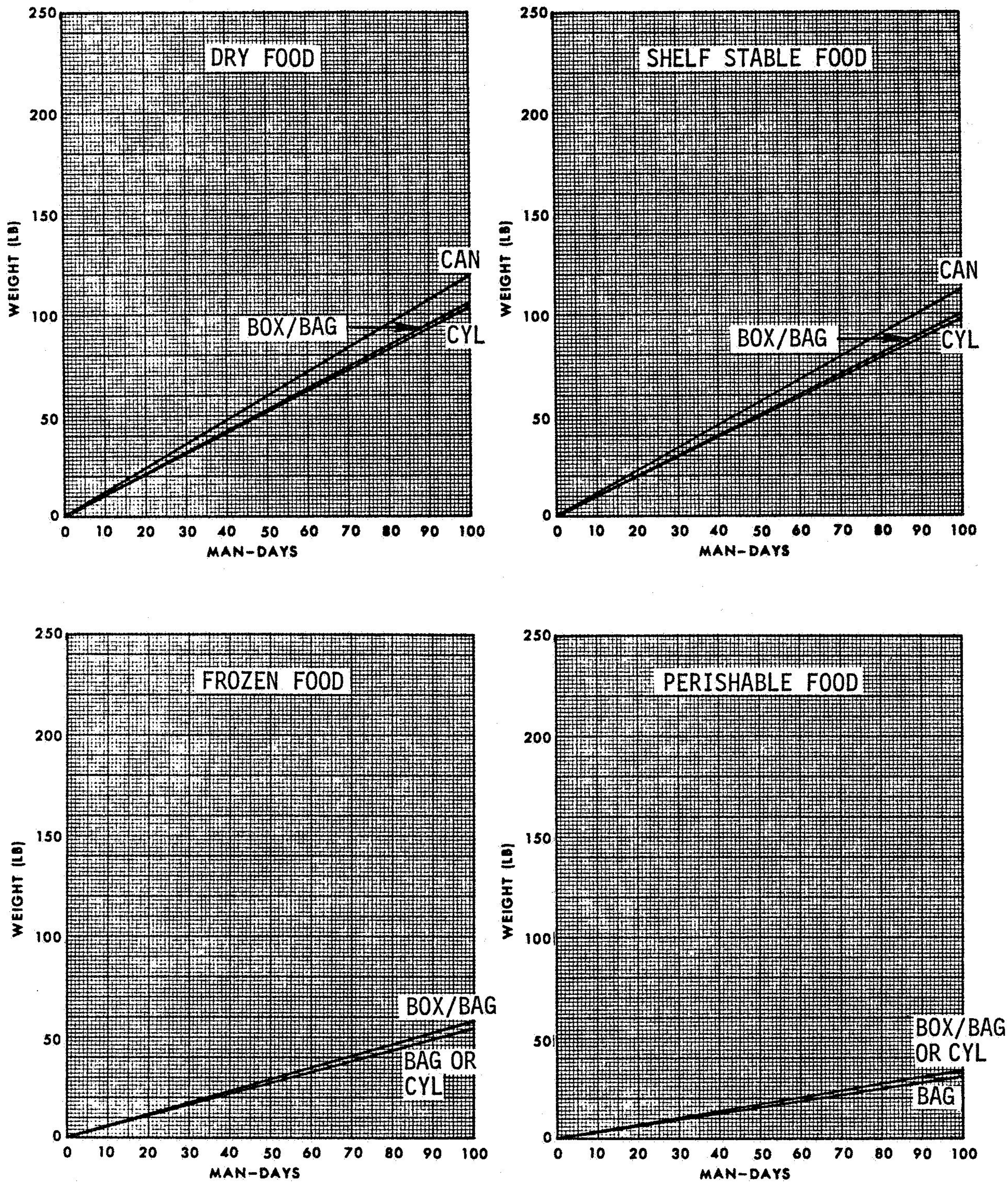


Figure 3-2. Packaged Food Weight for 60/40 Mix Ratio

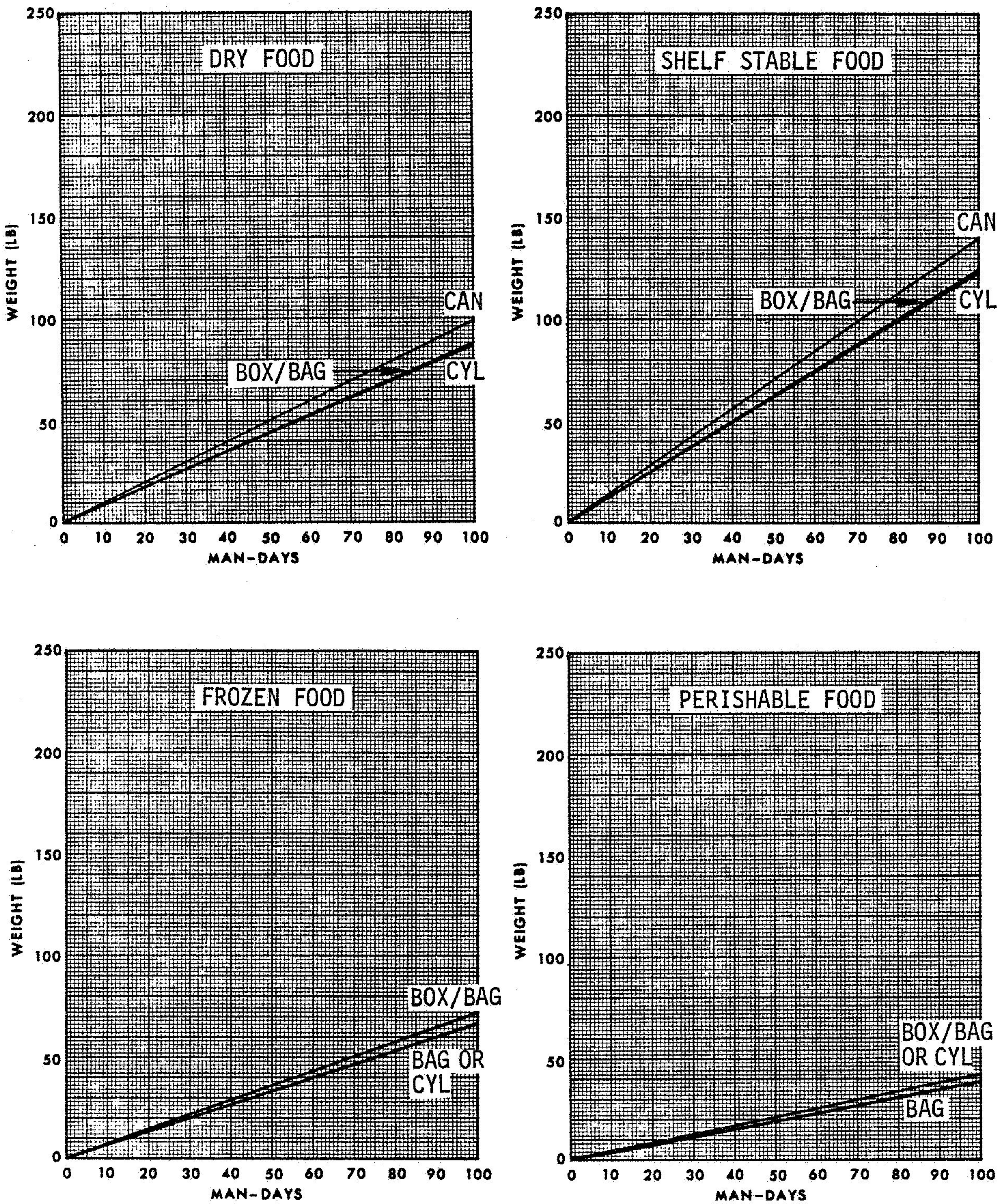


Figure 3-3. Packaged Food Weight for 50/50 Mix Ratio

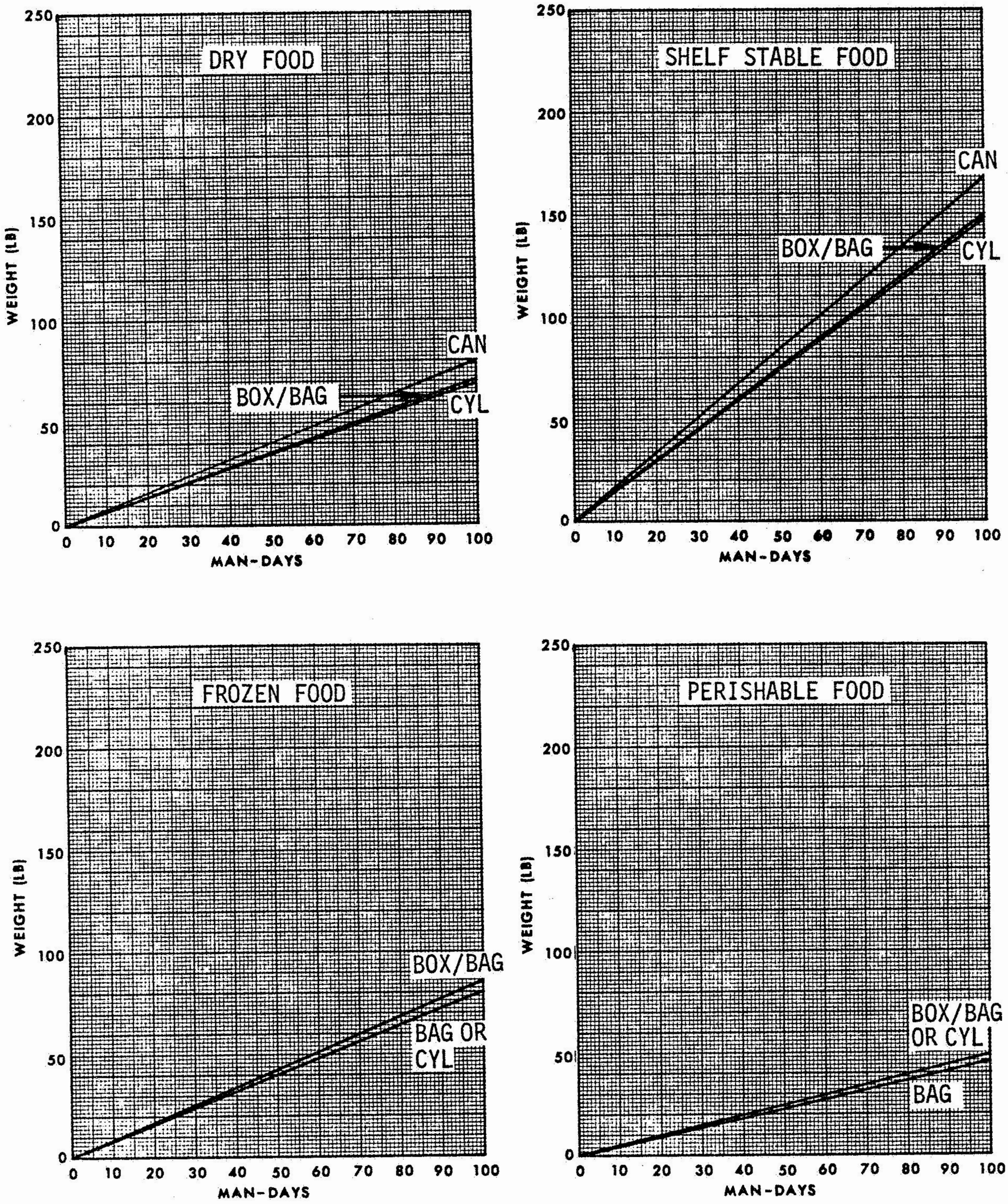


Figure 3-4. Packaged Food Weight for 40/60 Mix Ratio

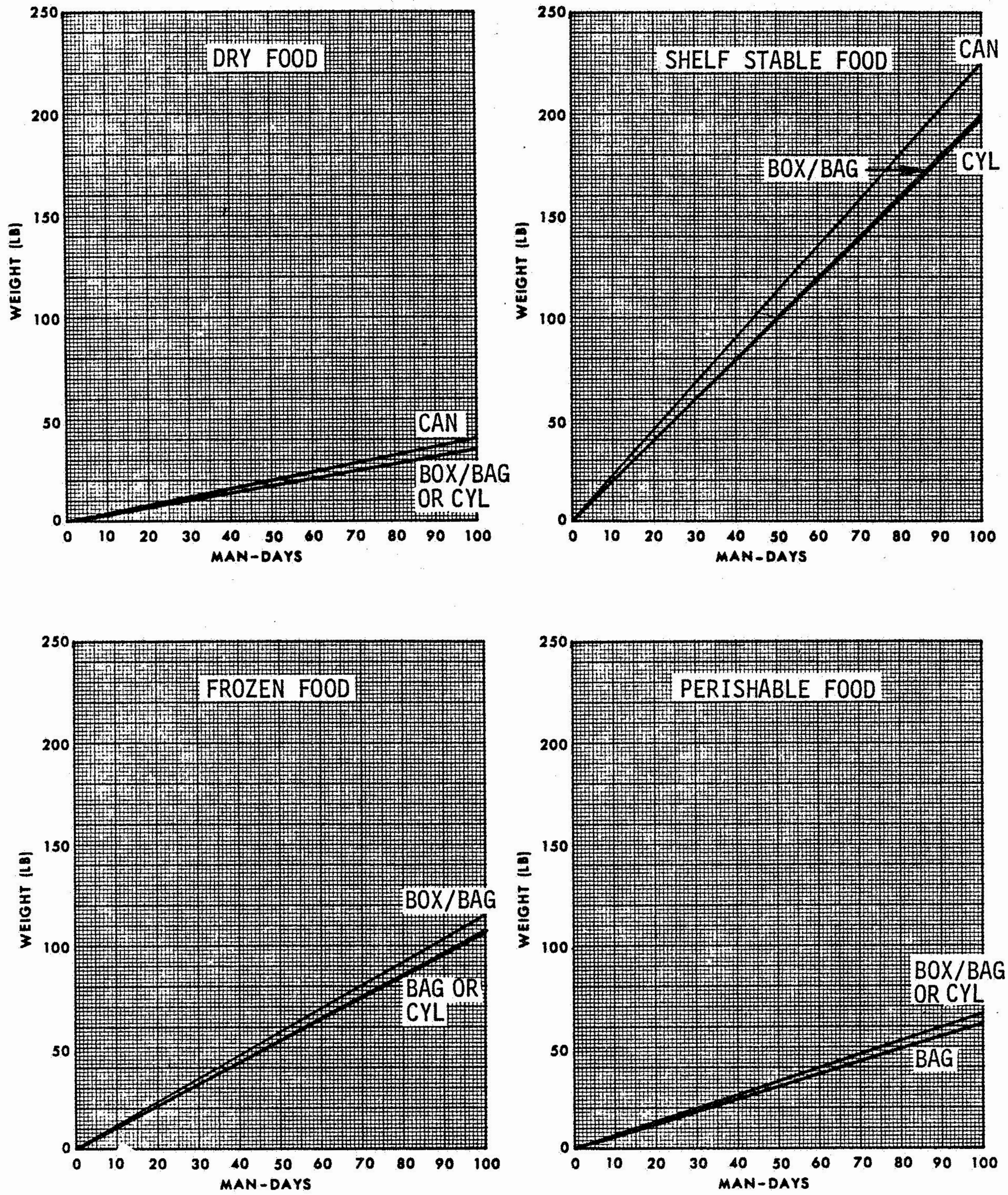


Figure 3-5. Packaged Food Weight for 20/80 Mix Ratio

3.3 PACKAGED FOOD VOLUME

Packaged food volume factors (ratio of package volume to wet weight of food) were derived for each package type and are presented in Table 3-3. Packaged food volumes per man-day were computed for each packaging technique and are presented in Table 3-4. Packaged food volumes were computed by the following method.

Packaged food volume = package volume factor x weight of food + volume of food

where:

Package volume factors are obtained from Table 3-3.

Food weights are obtained from Table 2-1.

Food volumes are obtained from Table 2-2.

Packaged food volume for any number of man-days may be obtained by multiplying by the desired number of man-days. Packaged food volume per man-days for each packaging method and food type are also presented in graphic form in Figures 3-6 through 3-10. These curves may be extended to any number of man-days and packaged volumes by multiplying the ordinate and abscissa by an appropriate factor, i.e., 10, 100, 1000.

Table 3-3. Food Package Volume Factors (Cubic Feet Package ÷ Pounds Food)

Food and Storage Type	Canned	Box and Bag	Bag	Cylindrical
Dry (Ambient)	0.023	0.061	N/A	0.018
Frozen (Freezer)	N/A	0.064	0.032	0.057
Shelf Stable (Ambient)	0.023	0.061	N/A	0.018
Perishable (Refrigerated)	N/A	0.069	0.037	0.022

Table 3-4. Packaged Food Volumes for Various Mix Ratios

Food and Package Type	Packaged Volume of Food for Various Mix Ratios (ft^3/man-day)				
	80/20	60/40	50/50	40/60	20/80
Dry Food					
Canned	0.079	0.059	0.049	0.039	0.020
Box and Bag	0.126	0.095	0.079	0.063	0.032
Bag	N/A	N/A	N/A	N/A	N/A
Cylindrical	0.073	0.054	0.045	0.036	0.018
Frozen Food					
Canned	N/A	N/A	N/A	N/A	N/A
Box and Bag	0.022	0.044	0.056	0.067	0.089
Bag	0.014	0.028	0.034	0.041	0.055
Cylindrical	0.020	0.041	0.051	0.061	0.082
Shelf Stable Food					
Canned	0.019	0.038	0.047	0.057	0.076
Box and Bag	0.036	0.071	0.089	0.107	0.143
Bag	N/A	N/A	N/A	N/A	N/A
Cylindrical	0.017	0.033	0.042	0.050	0.067
Perishable Food					
Canned	N/A	N/A	N/A	N/A	N/A
Box and Bag	0.015	0.031	0.038	0.046	0.061
Bag	0.011	0.021	0.026	0.032	0.042
Cylindrical	0.008	0.017	0.021	0.025	0.033

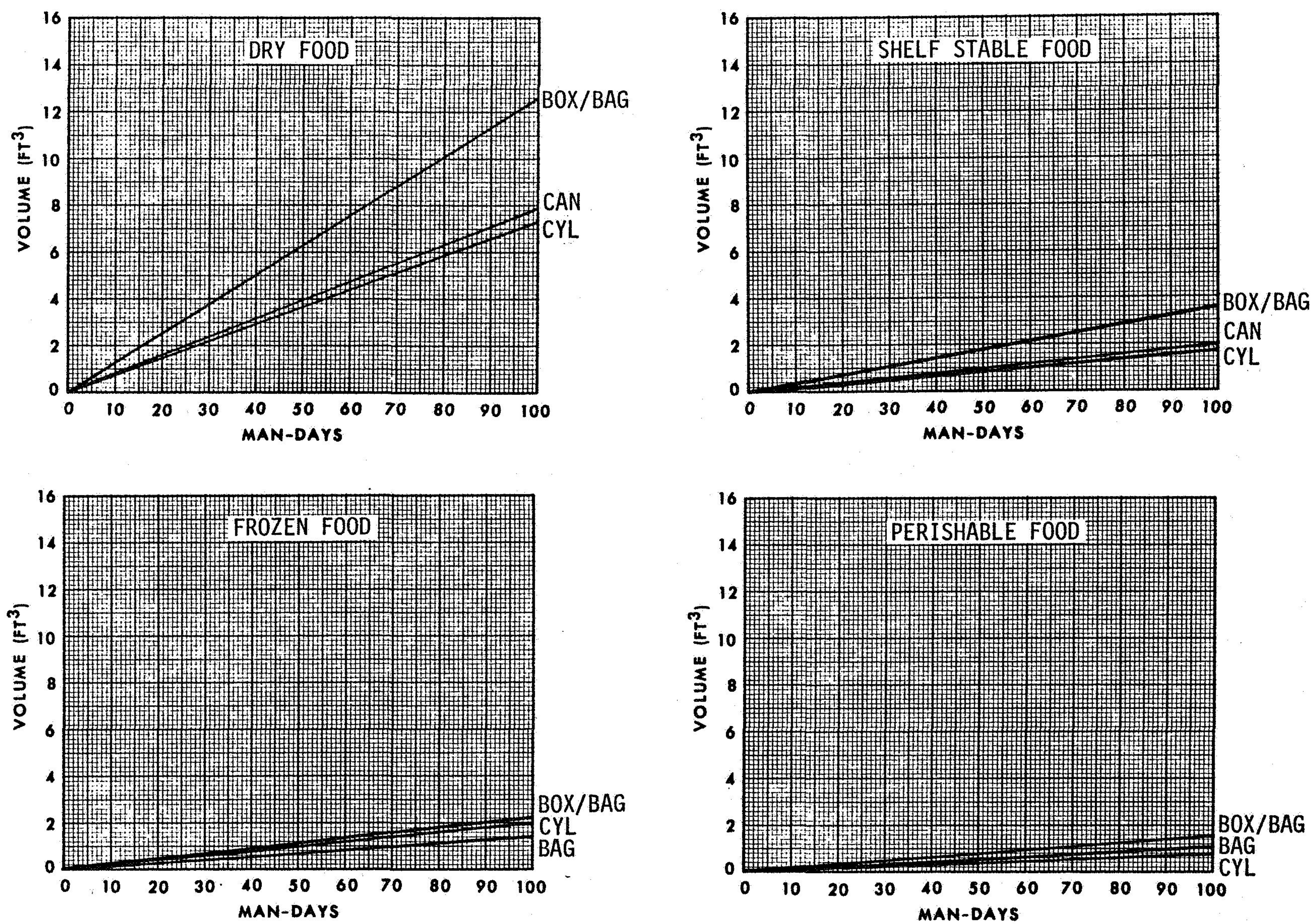


Figure 3-6. Food Volume for 80/20 Mix Ratio

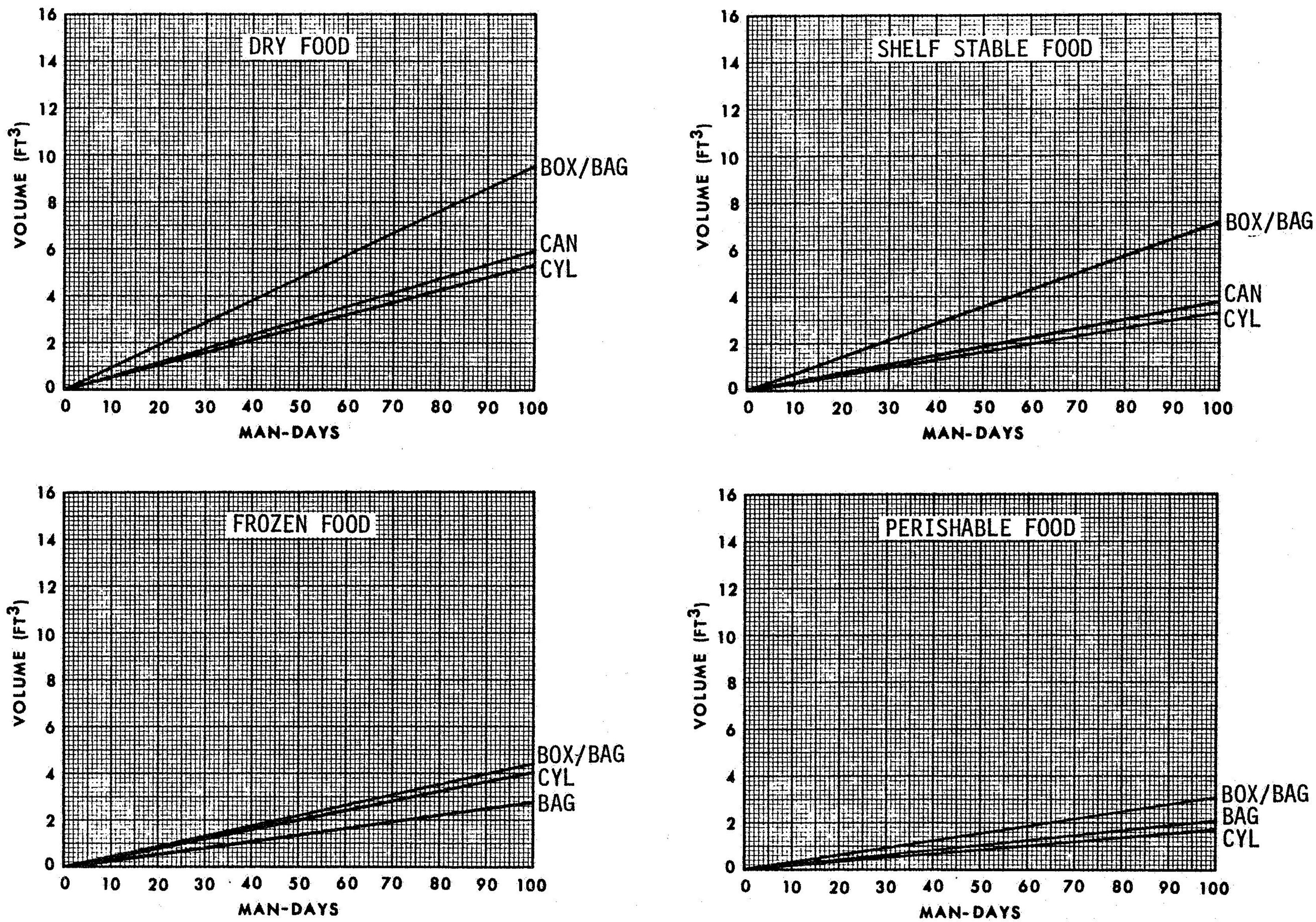


Figure 3-7. Food Volume for 60/40 Mix Ratio

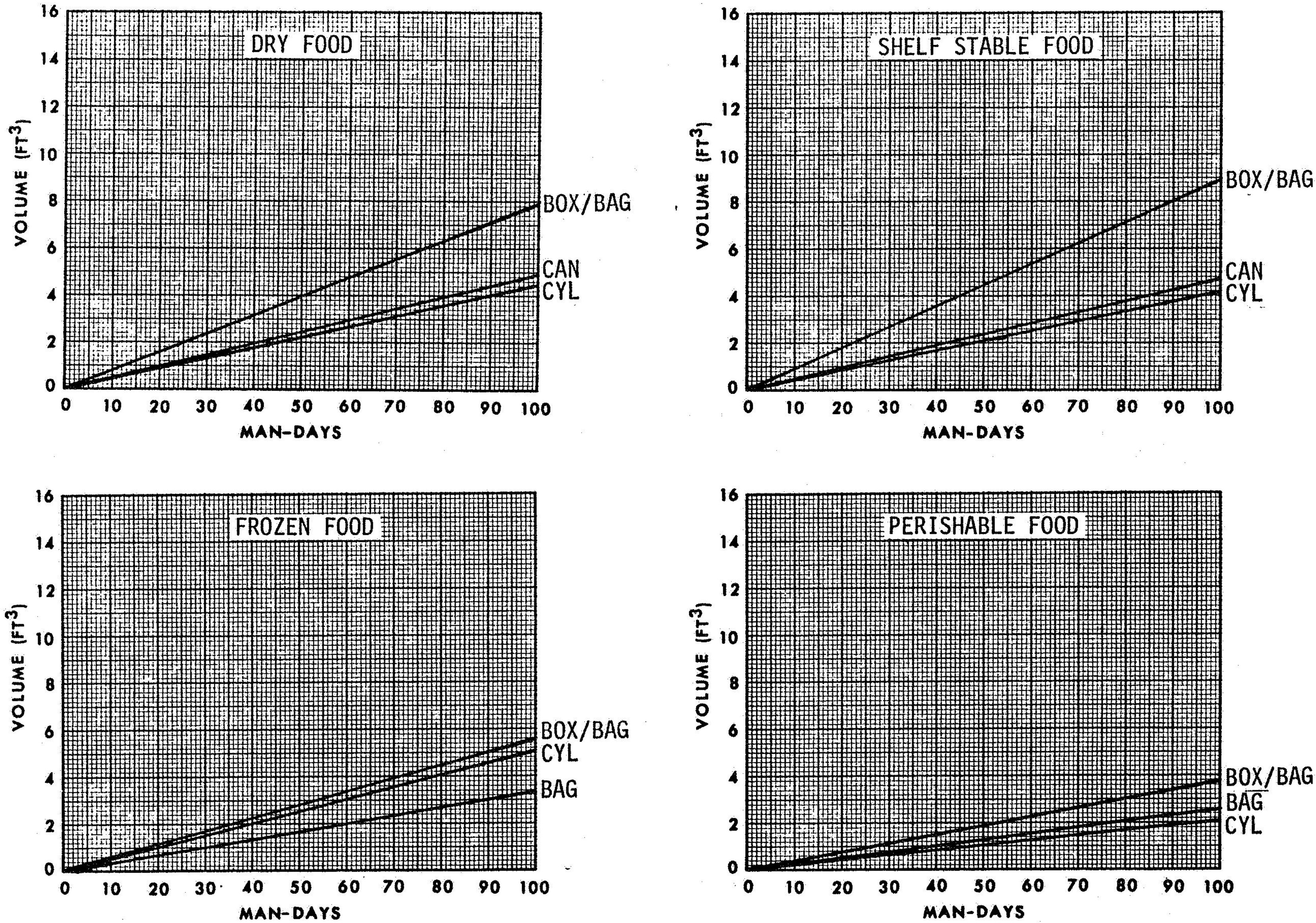


Figure 3-8. Food Volume for 50/50 Mix Ratio

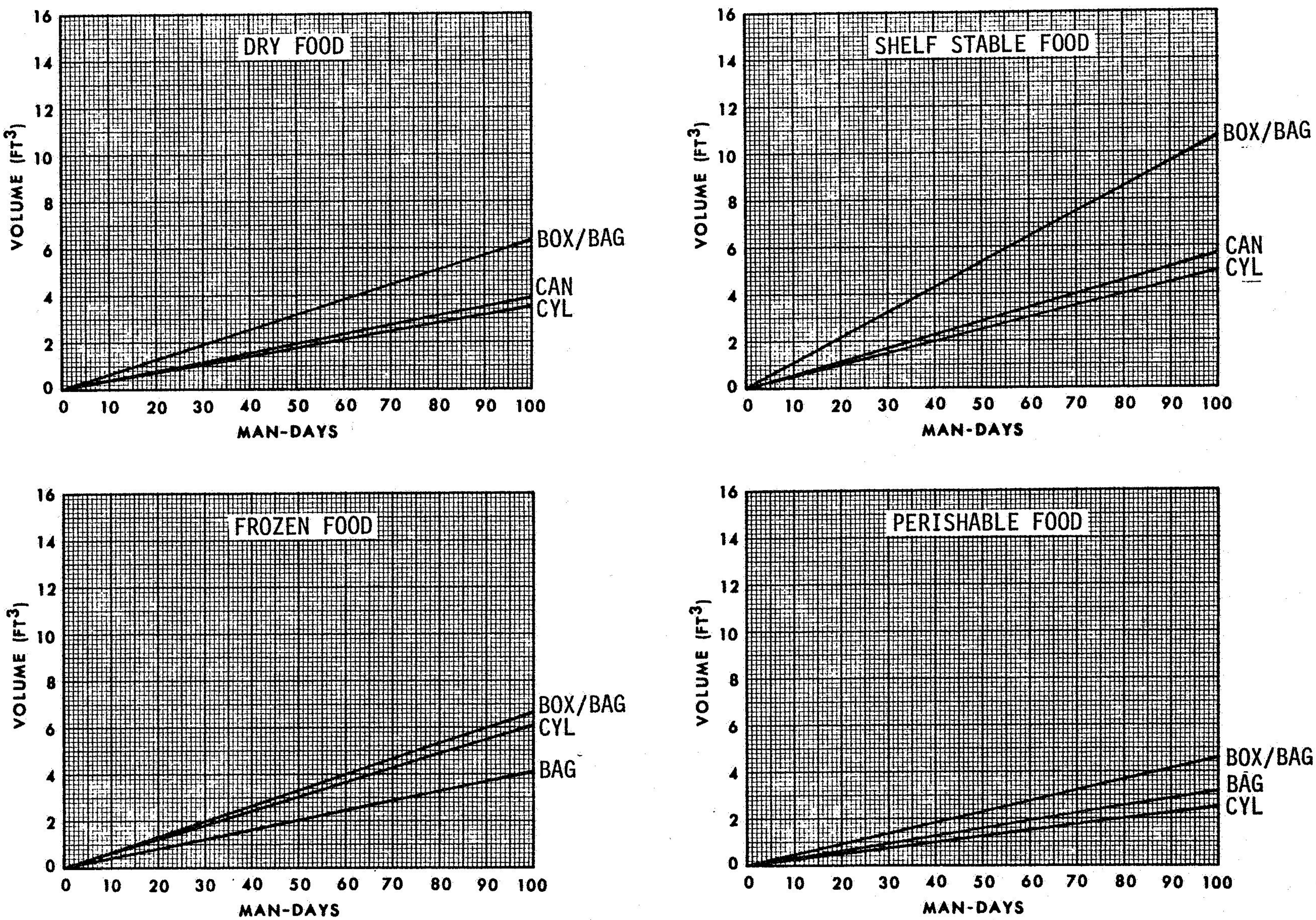


Figure 3-9. Food Volume for 40/60 Mix Ratio

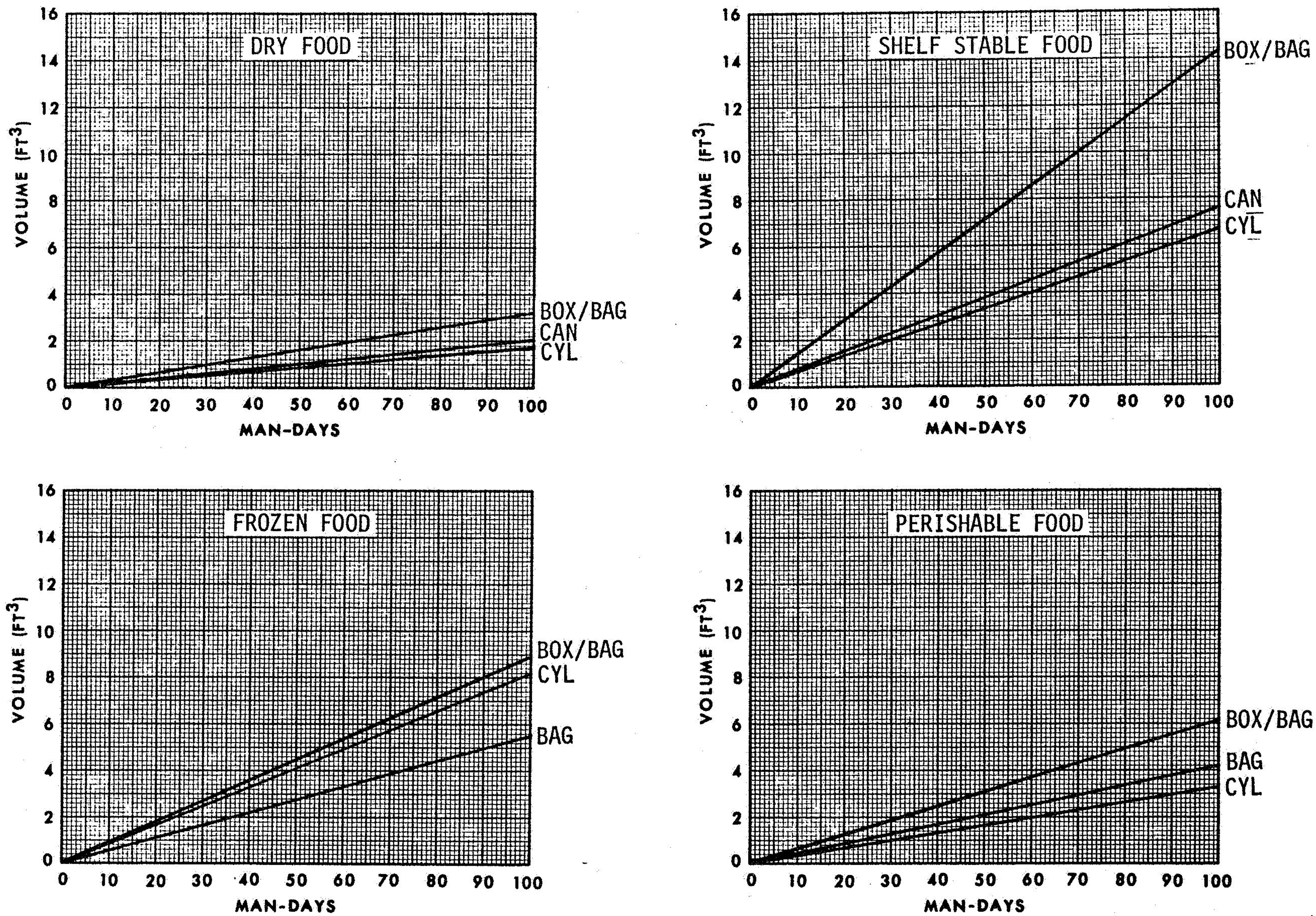


Figure 3-10. Food Volume for 20/80 Mix Ratio

4.0 FOOD STORAGE

4.1 REFRIGERATOR/FREEZER CONCEPTS AND ENGINEERING DATA

The three concepts presented in this paragraph are: a) the Space Radiator, b) the Thermoelectric System, and c) the Turbo-Compressor/Air Cycle System.

Space Radiator (Figure 4-1)

The space radiator system relies on a suitable coolant circulated through coils located within the refrigerator/freezer storage compartment. Heat is absorbed by the coolant from the storage compartment and transferred to space radiator heat exchangers located on the outer surface of the spacecraft.

Engineering Data*

Locker heat losses for given capacities	Figure 4-2
Installed locker weights for given capacities	Figure 4-3
Installed locker volumes for given capacities	Figure 4-4

Nominal design temperatures

Refrigerator interior	= 40°F
Freezer interior	= -10°F
Ambient	= 75°F
Background	= 80°F

Heat loss per ft^2 of exterior surface

Refrigerator	= 2.065 Btu/hr
Freezer	= 5.040 Btu/hr

Power for refrigerator or freezer

Maximum	= 50 watts
Average	= 3.08 watt-hrs/day

Insulation

4 in. of foam for refrigerator or freezer

*Sample calculations are presented in Appendix A

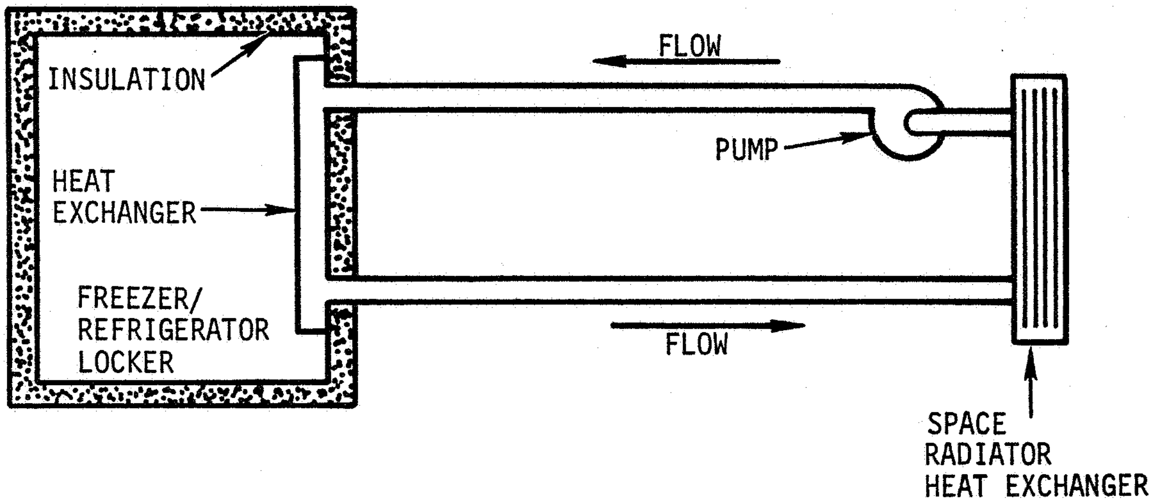


Figure 4-1. Space Radiator

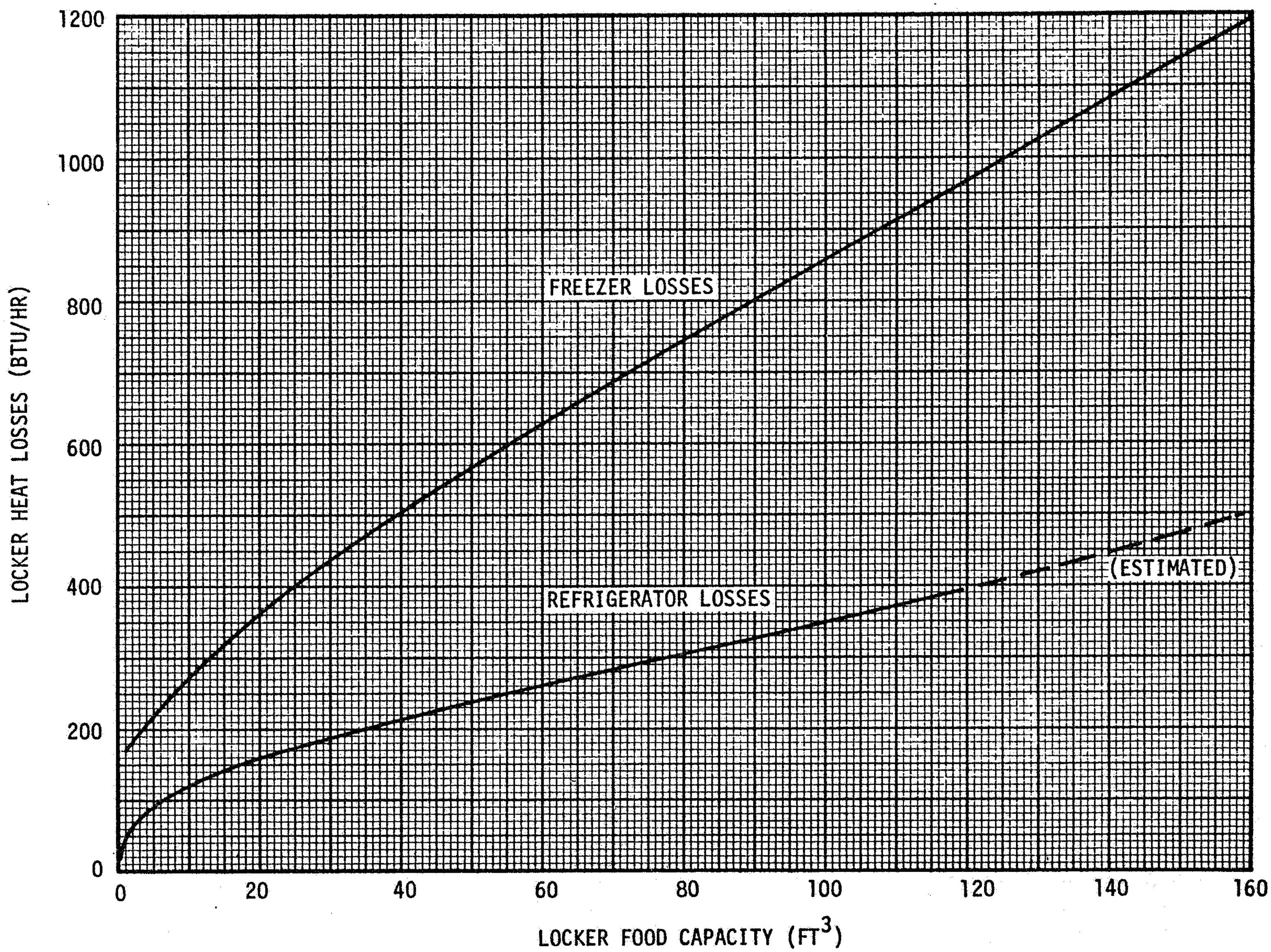


Figure 4-2. Space Radiator Locker Heat Losses for Various Capacities

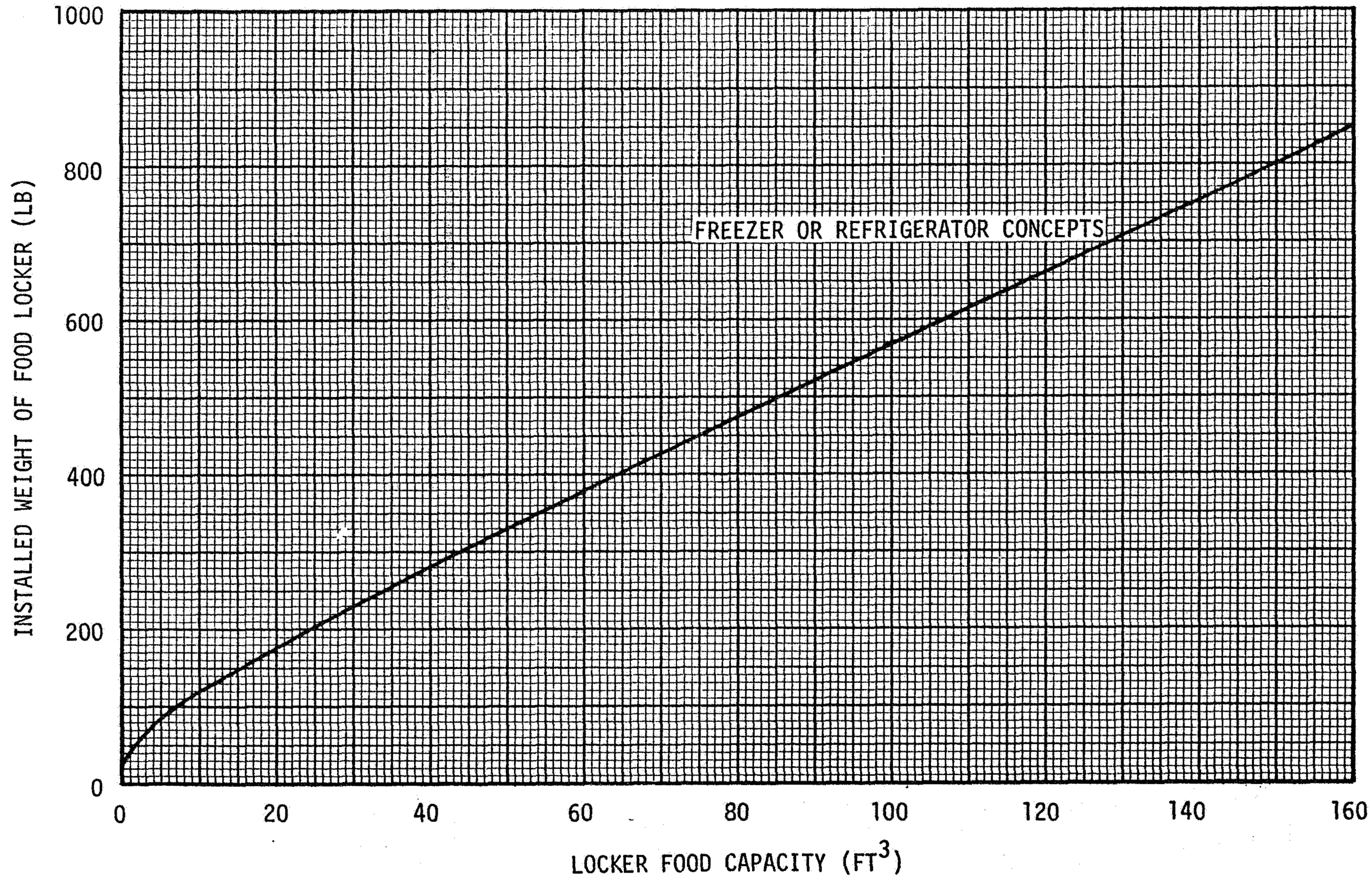


Figure 4-3. Space Radiator Locker Weight for Various Capacities

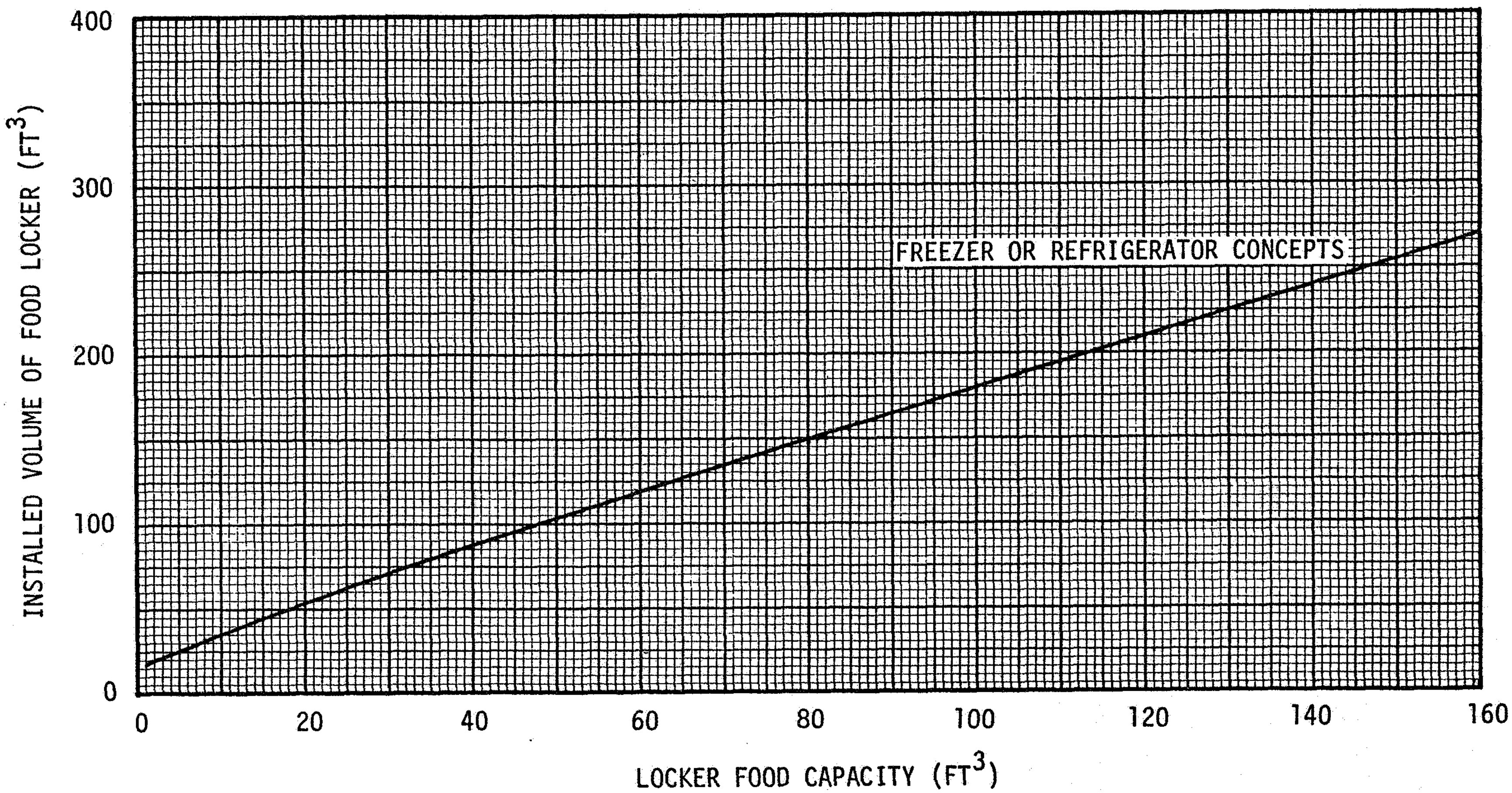


Figure 4-4. Space Radiator Locker Volume for Various Capacities

Thermoelectric System (Figure 4-5)

The thermoelectric refrigerator/freezer is a solid-state module that transfers heat from its colder junction (a plate that absorbs heat from the load) to a hot junction (a heat sink where heat is rejected) using electrical energy to sustain the heat flow. Forced convection air-cooled fins or a liquid-cooled sink must be used to remove heat energy from the hot junction to allow it to operate at predesigned temperature levels.

Engineering Data*

Installed locker weights for given capacities	Figure 4-6

Nominal Design Temperature

Refrigerator interior	=	40°F
Freezer interior	=	-10°F
Ambient	=	75°F
Background	=	80°F

Locker heat loss per ft^2 of exterior surface

Refrigerator	=	2.065 Btu/hr
Freezer	=	5.040 Btu/hr

Locker heat losses for given capacities	Figure 4-7
Installed locker weights versus heat loss	Figure 4-8
Installed locker volumes versus heat loss	Figure 4-9
Power versus locker heat loss	Figure 4-10

Insulation

4 in. of foam for refrigerator or freezer

*Sample calculations are presented in Appendix A.

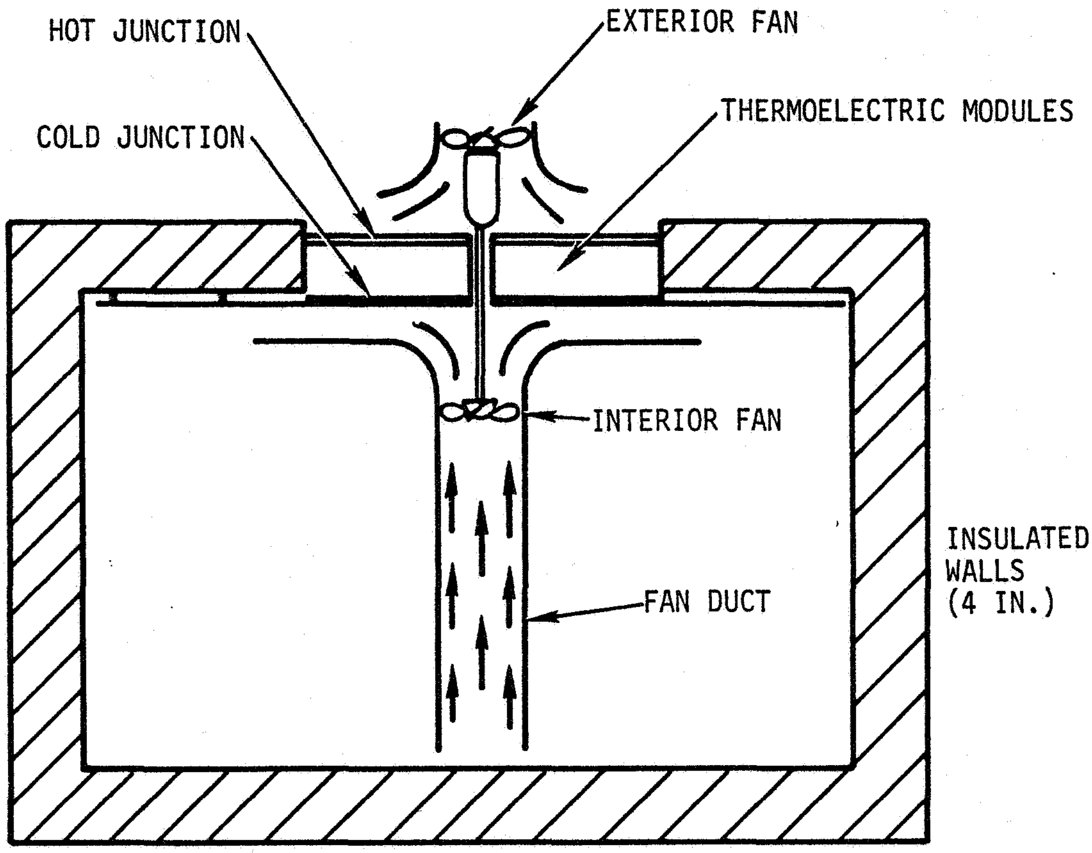


Figure 4-5. Thermoelectric Freezer or Refrigerator

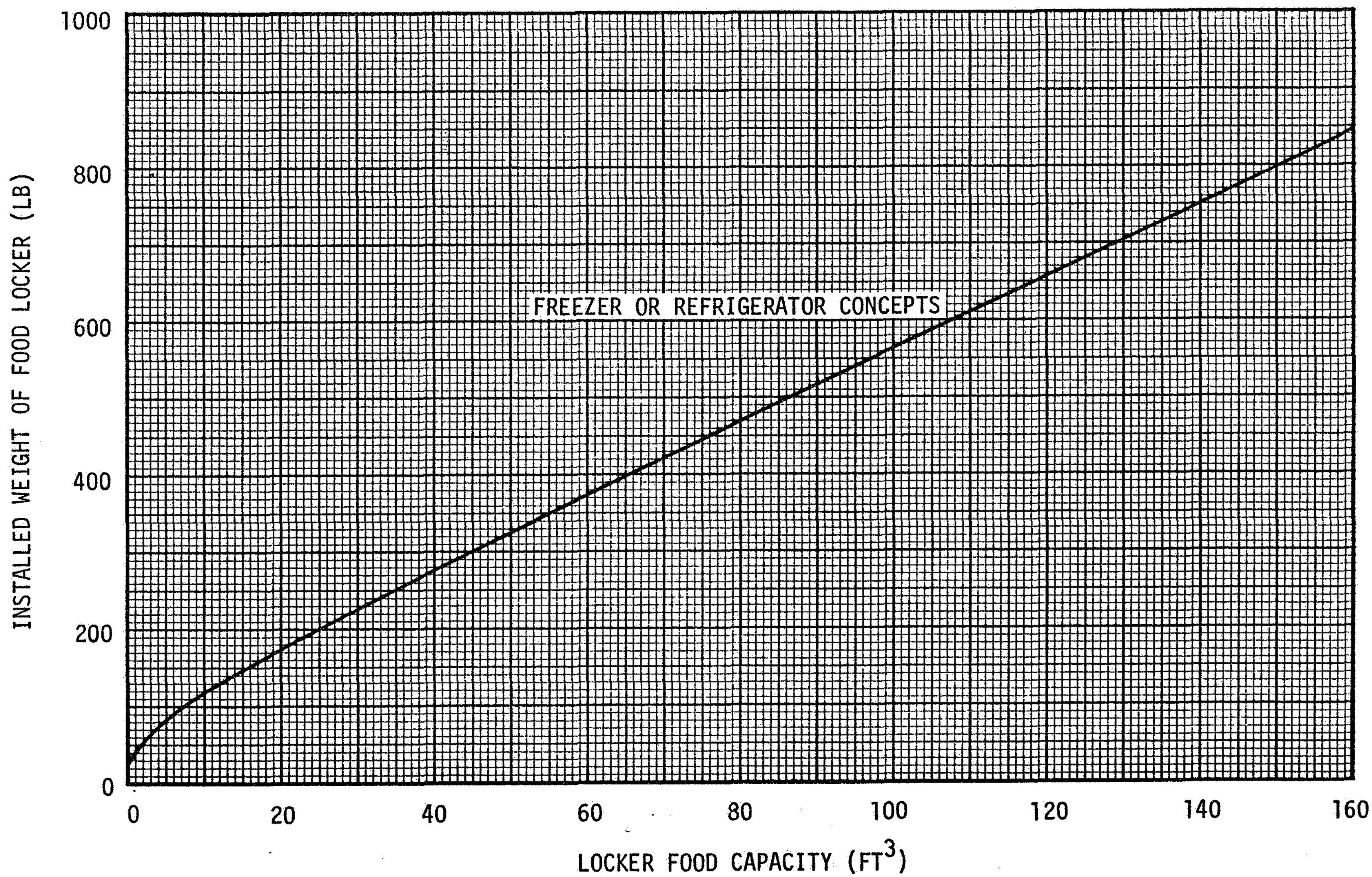


Figure 4-6. Thermoelectric Locker Weight for Various Capacities

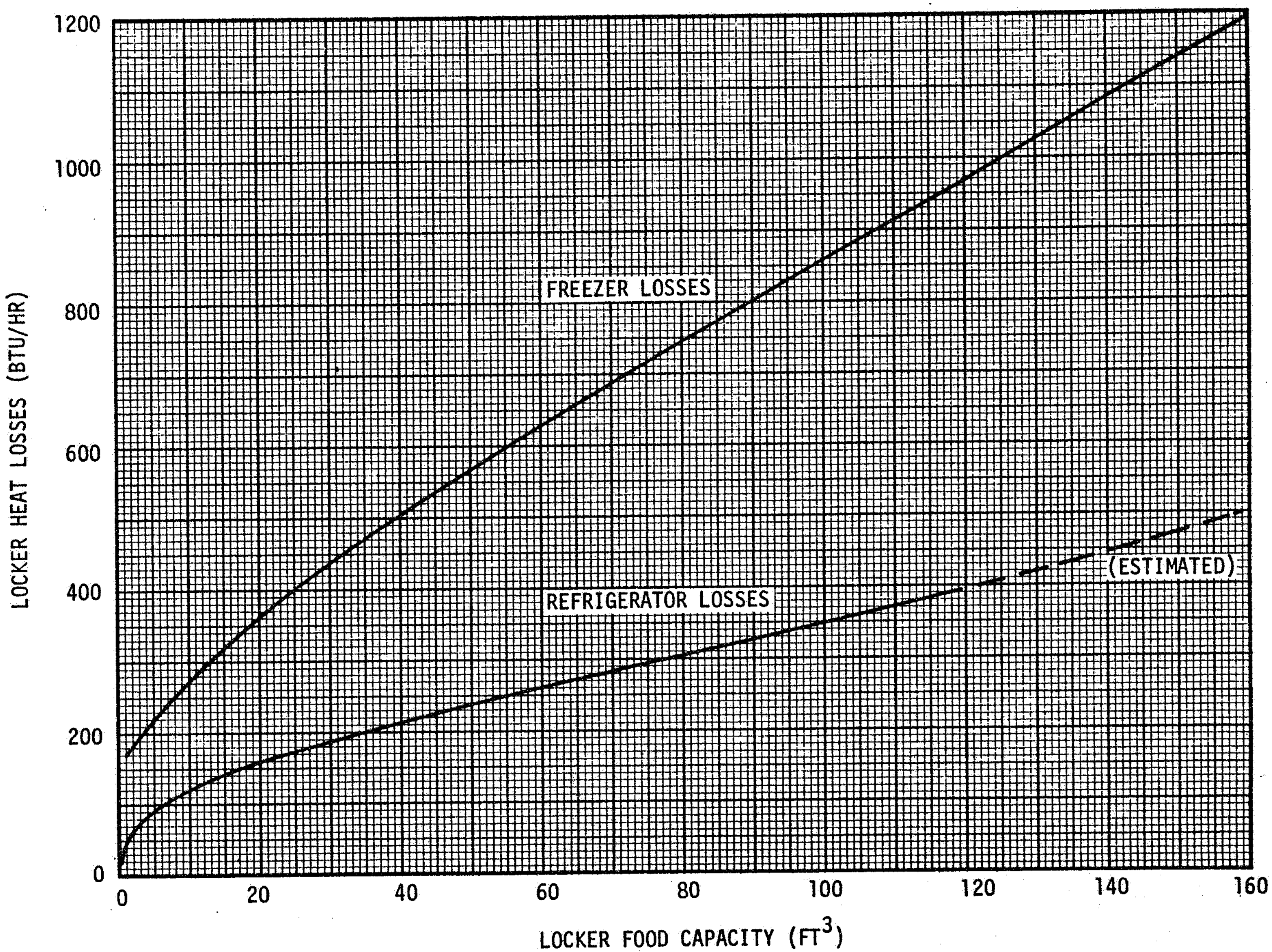


Figure 4-7. Thermoelectric Locker Heat Losses for Various Capacities

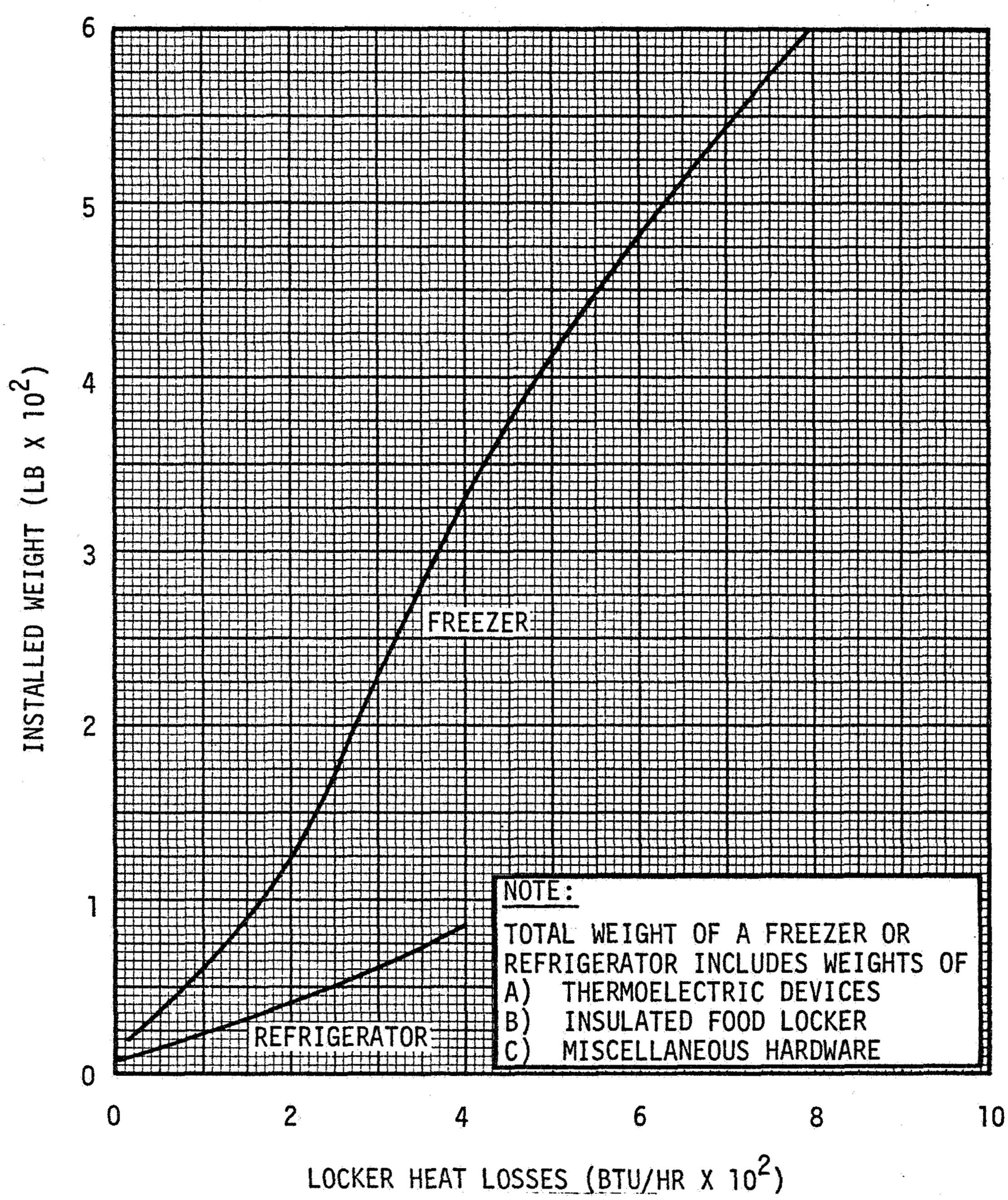


Figure 4-8. Weights of Thermoelectric Devices for Various Locker Heat Losses

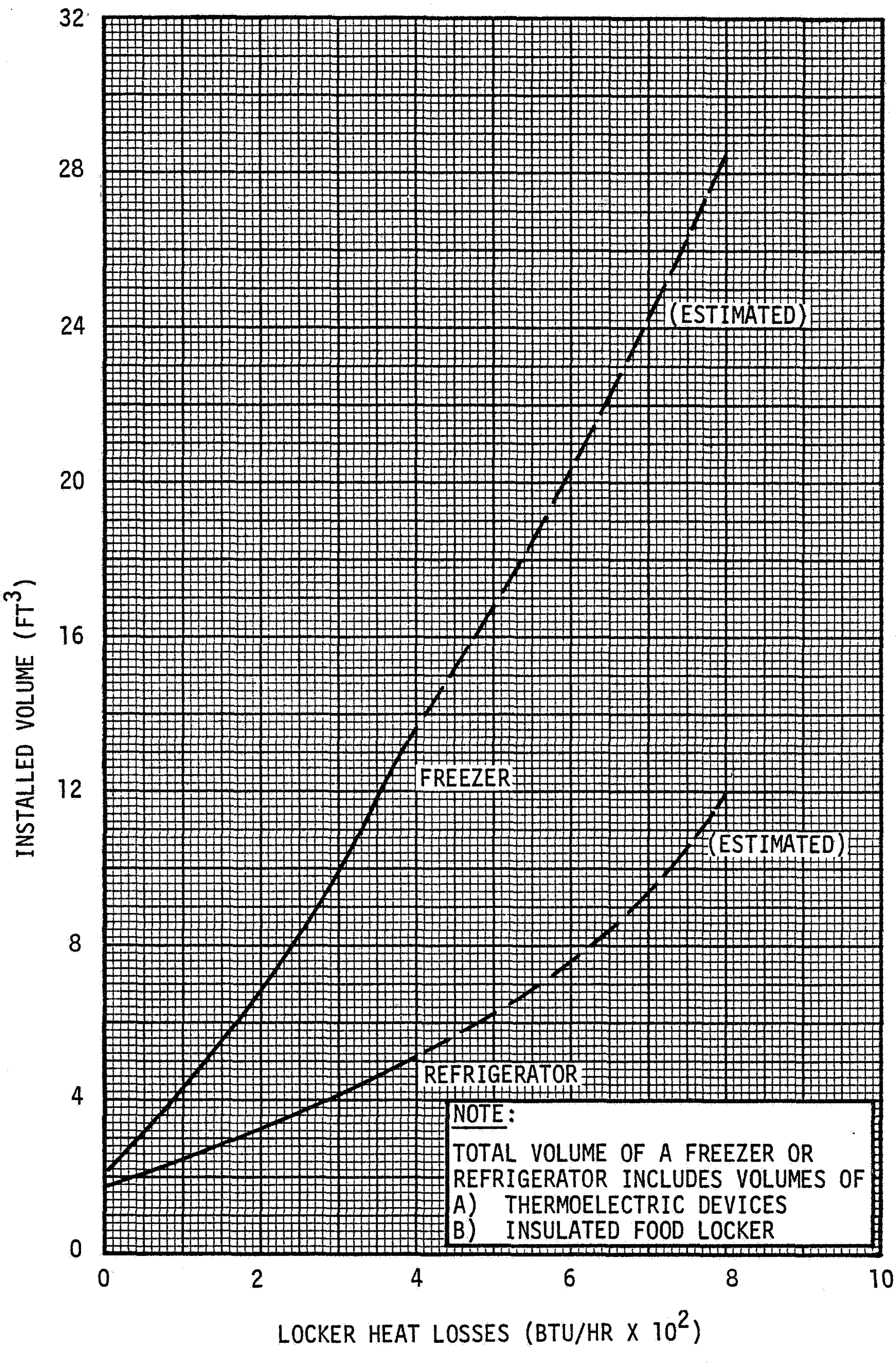


Figure 4-9. Volume of Thermoelectric Device for Various Heat Losses

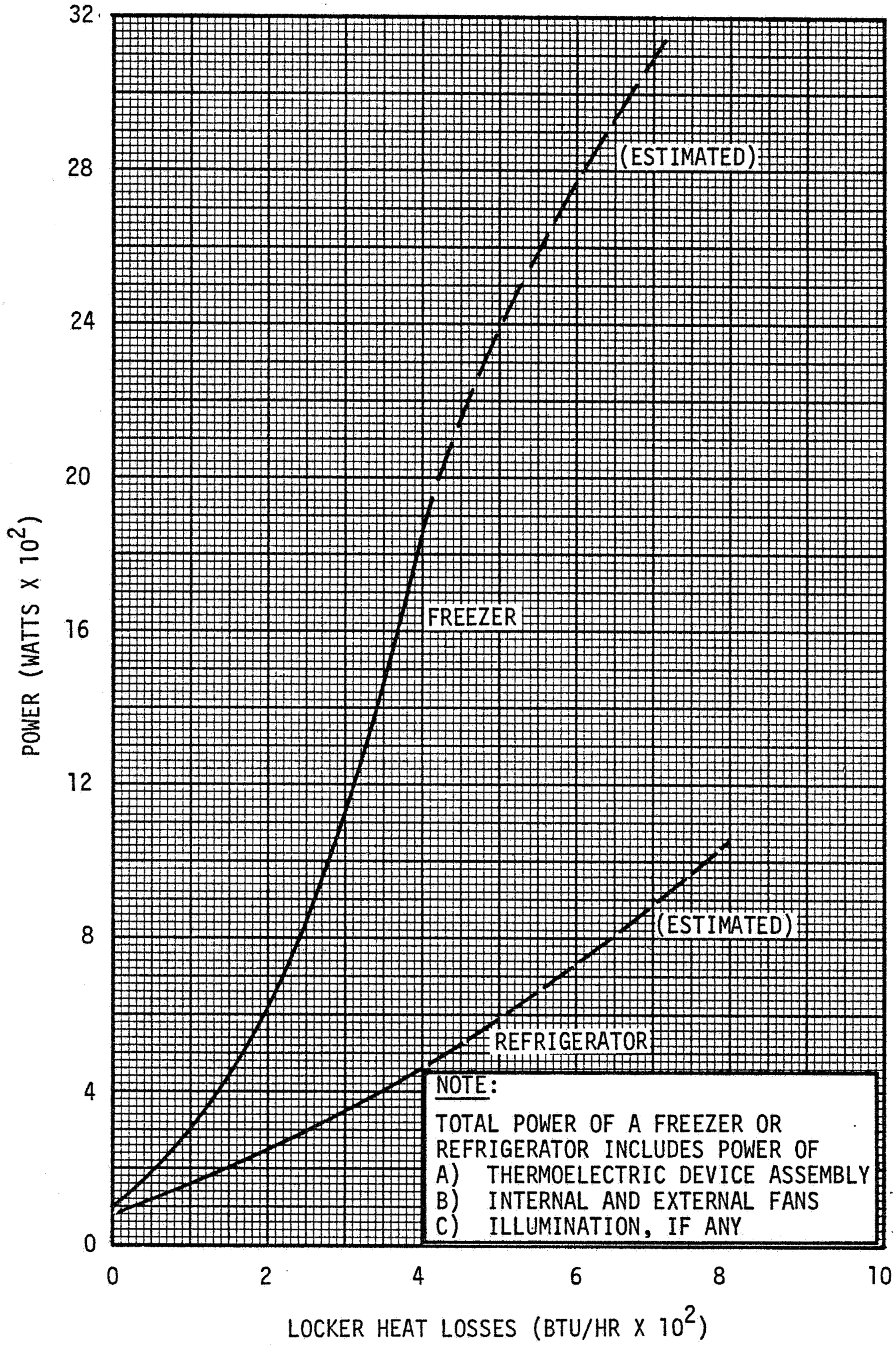


Figure 4-10. Power Required for Thermoelectric Device for Various Heat Losses

Turbo-Compressor/Air Cycle (Figure 4-11)

The turbo-compressor/air cycle refrigerator/freezer utilizes air as a refrigerant. Air is compressed in a turbo-compressor, forced through a heat exchanger, and allowed to expand. The expanding air is ducted to the insulated interior of the unit and provides cooling and circulation simultaneously.

Engineering Data*

Installed refrigerator volume for given capacities	Figure 4-12
Installed refrigerator weight for given capacities	Figure 4-12
Installed refrigerator power for given capacities	Figure 4-12
Installed freezer volume for given capacities	Figure 4-13
Installed freezer weight for given capacities	Figure 4-13
Installed freezer power for given capacities	Figure 4-13

Nominal design temperature

Refrigerator interior	=	40°F
Freezer interior	=	-10°F
Ambient	=	75°F
Background	=	80°F

Heat loss per ft^2 of external surface

Refrigerator	=	2.065 Btu/hr
Freezer	=	5.040 Btu/hr

Insulation

4 in. of foam for refrigerator or freezer

*Sample calculations are presented in Appendix A.

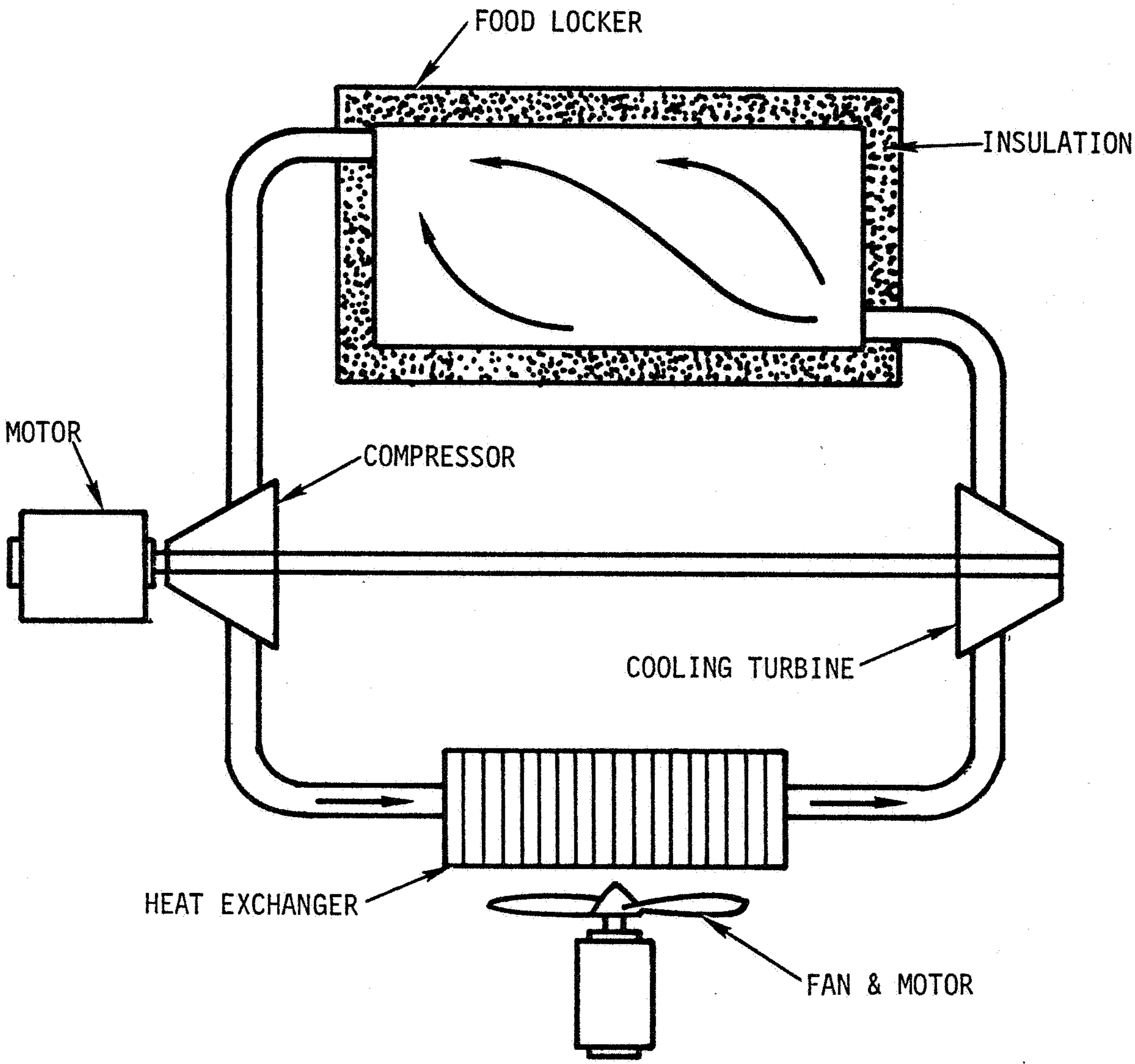


Figure 4-11. Turbo-Compressor/Air Cycle Refrigerator/Freezer

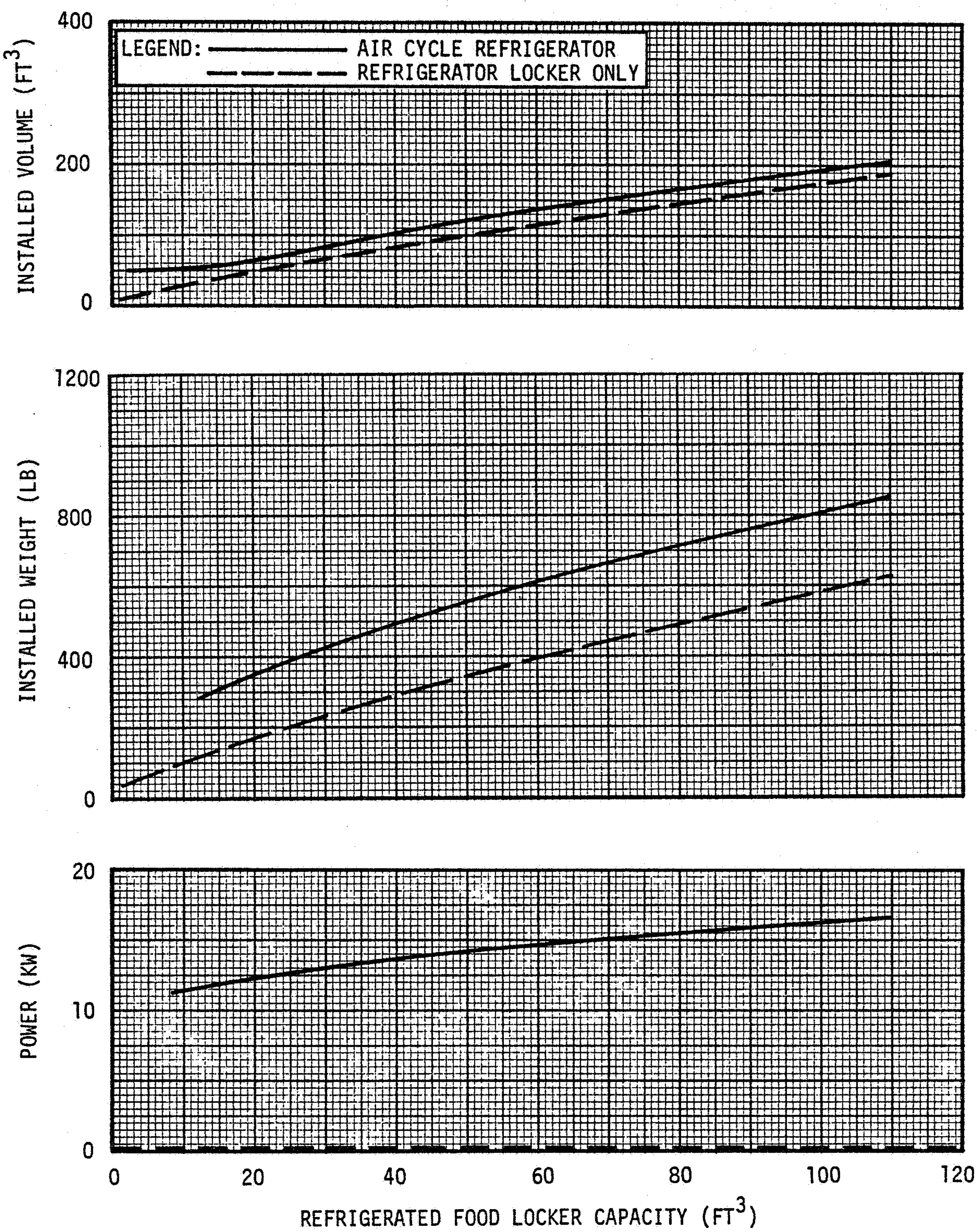


Figure 4-12. Air Cycle Power, Weight and Volume for Various Refrigerator Food Capacities

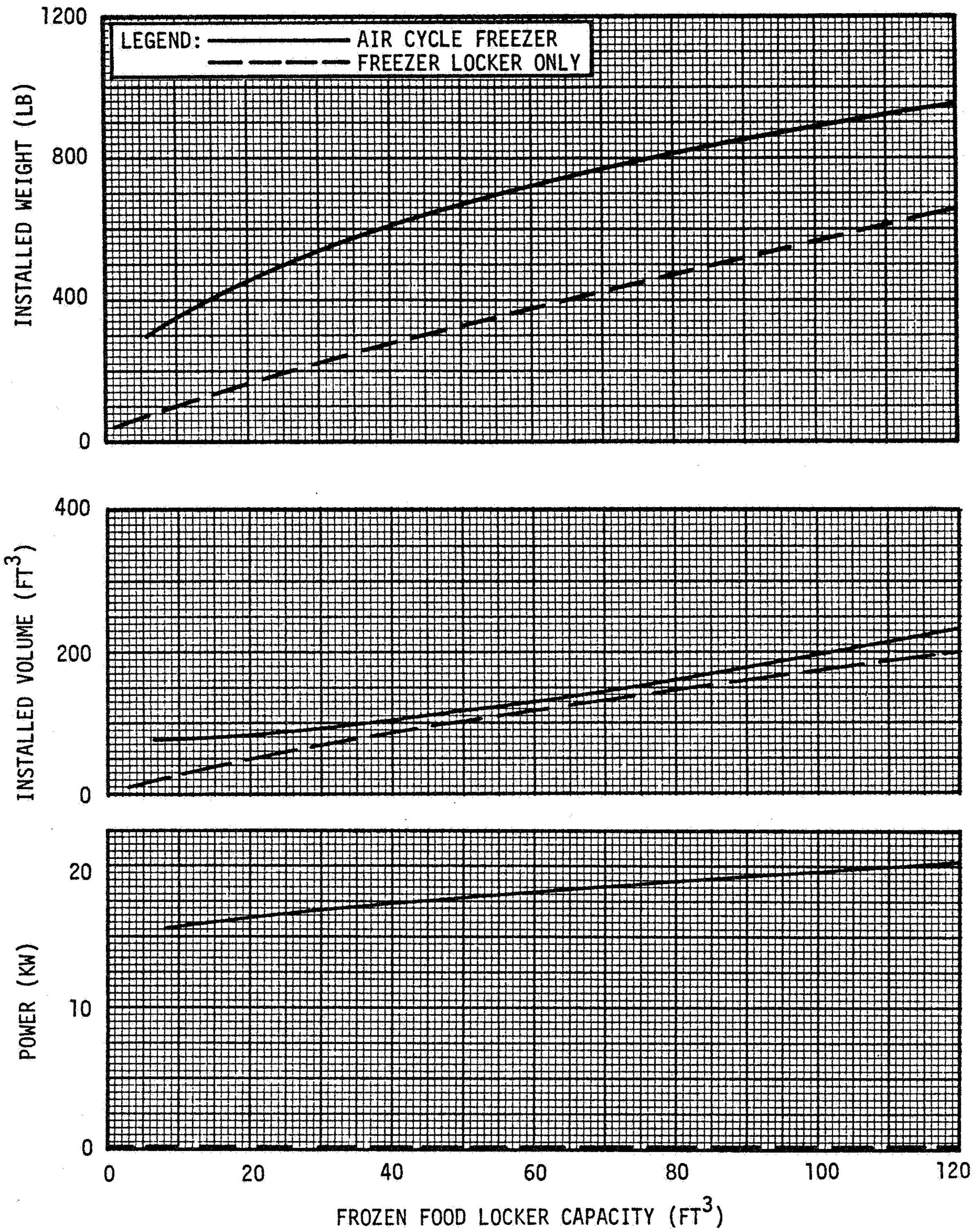


Figure 4-13. Air Cycle Power, Weight and Volume for Various Freezer Capacities

4.2 AMBIENT STORAGE*

4.2.1 Volume Requirements. Ambient storage is suitable for storing dry and shelf-stable foods. The total percentage of food requiring ambient storage for the shelf stable and dry food ratios considered in this handbook are presented in Table 4-12.

Table 4-12. Percent of Food Requiring Ambient Storage

Food Mix Ratios Dry/Wet (%)	Dry Food	Shelf Stable Food (50% of Wet Portion)	Percent of Food in Ambient Storage
80/20	80%	10%	90%
60/40	60%	20%	80%
50/50	50%	25%	75%
40/60	40%	30%	70%
20/80	20%	40%	60%

Ambient storage volume factors per man-day were computed for the different packaging methods and are listed in Table 4-13. Packaged food storage volumes for any number of man-days may be obtained by multiplying by the desired number of man-days. The packaged volumes were computed by the following method.

Packaged food volume for ambient storage = packaged volume factor x (weight of dry food + weight of shelf stable food) + volume of dry food + volume of shelf stable food

where:

Packaged volume factors are obtained from Table 3-3.

Weights for dry and shelf stable food are obtained from Table 2-1.

Volumes for dry and shelf stable food are obtained from Table 2-2.

*Ambient storage at a nominal ambient temperature of 75°F is assumed.

Table 4-13. Ambient Storage Volume Factors

Food Mix Ratio	Total Food Weight (lb)	Total Food Volume (ft^3)	Storage Volume Required/Man-Day (ft^3) Canned	Box & Bag	Cylindrical
80/20	1.691	0.0588	0.0977	0.1620	0.0892
60/40	1.820	0.0551	0.0970	0.1661	0.0879
50/50	1.884	0.0533	0.0967	0.1682	0.0872
40/60	1.949	0.0515	0.0963	0.1704	0.0866
20/80	2.078	0.0478	0.0956	0.1746	0.0852

The comparative storage volumes per man-days for each packaging method and food mix ratio are also provided in graphic form in Figure 4-14. These curves may be extended to any number of man-days and volumes by multiplying the ordinate and abscissa by an appropriate factor, i.e., 10, 100, 1000.

4.2.2 Concepts

Storage Locker/Room

A rigid storage locker or room will provide adequate ambient storage. Food packages could be stacked in a predetermined arrangement on shelves using suitable retention means. See Volume I, Mobility and Restraint, for additional data on devices and techniques for restraint.

Flexible Storage

Flexible ambient storage will consist of an elastic netting material or extendible membrane fastened to a convenient bulkhead or deck in the vehicle. When not in use, the flexible container can be collapsed to a minimal volume.

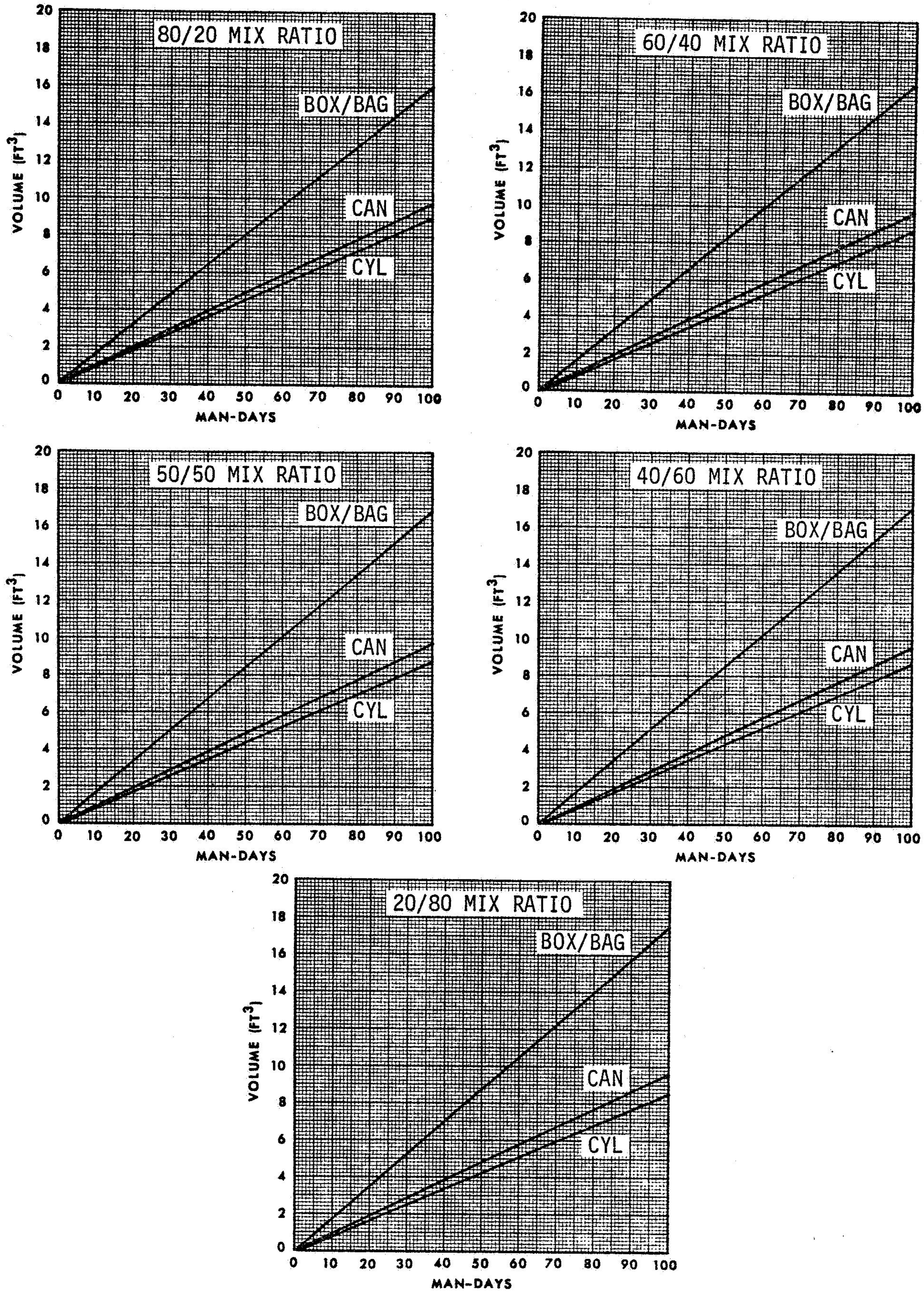


Figure 4-14. Ambient Storage Volume Factors for Various Mix Ratios

5.0 FOOD PREPARATION

5.1 WEIGHT, VOLUME AND POWER REQUIREMENTS

The weight, volume and power requirements for ovens used to warm food from -10°F to 160°F are based on a warming oven sized to accommodate 80 percent of the allotted frozen food per man-day. The largest quantity of frozen food is found in the 20/80 mix ratio (reference Section 2, Table 2-1). By assuming these worst case conditions, the data presented in this section will be adequate for the other food mix ratios considered.

Weight of food to be warmed per meal: 0.8 x 1.059 lb = 0.8472 lb
Volume of food to be warmed per meal: 0.8 x 0.212 ft^3 = 0.1696 ft^3

5.2 HEATING CONCEPTS AND ENGINEERING DATA

The heating concepts discussed in this paragraph are: a) the Hot Air Convection Heating Oven, b) the Microwave Heating Oven, c) the Resistance Heating Oven, d) the Self-Heating Food Package, e) the Combination Hot Air Convection and Resistance Heating Oven, and g) the Electrically Heated Food Tray.

Hot Air Convection Heating Oven

Air heated to 375 ($\pm$ 25)°F is circulated through the insulated food compartment. The heated air impinges upon the external surface of the food container and raises the food temperature. Air circulation is accomplished with a fan or blower.

<u>Engineering Data*</u>

Food temperature

Frozen = -10°F
Prepared = 160°F

Installed volume vs crew size	Figure 5-1
Installed weight vs crew size	Figure 5-1
Power required vs crew size	Figure 5-1

*Sample computations are presented in Appendix A.

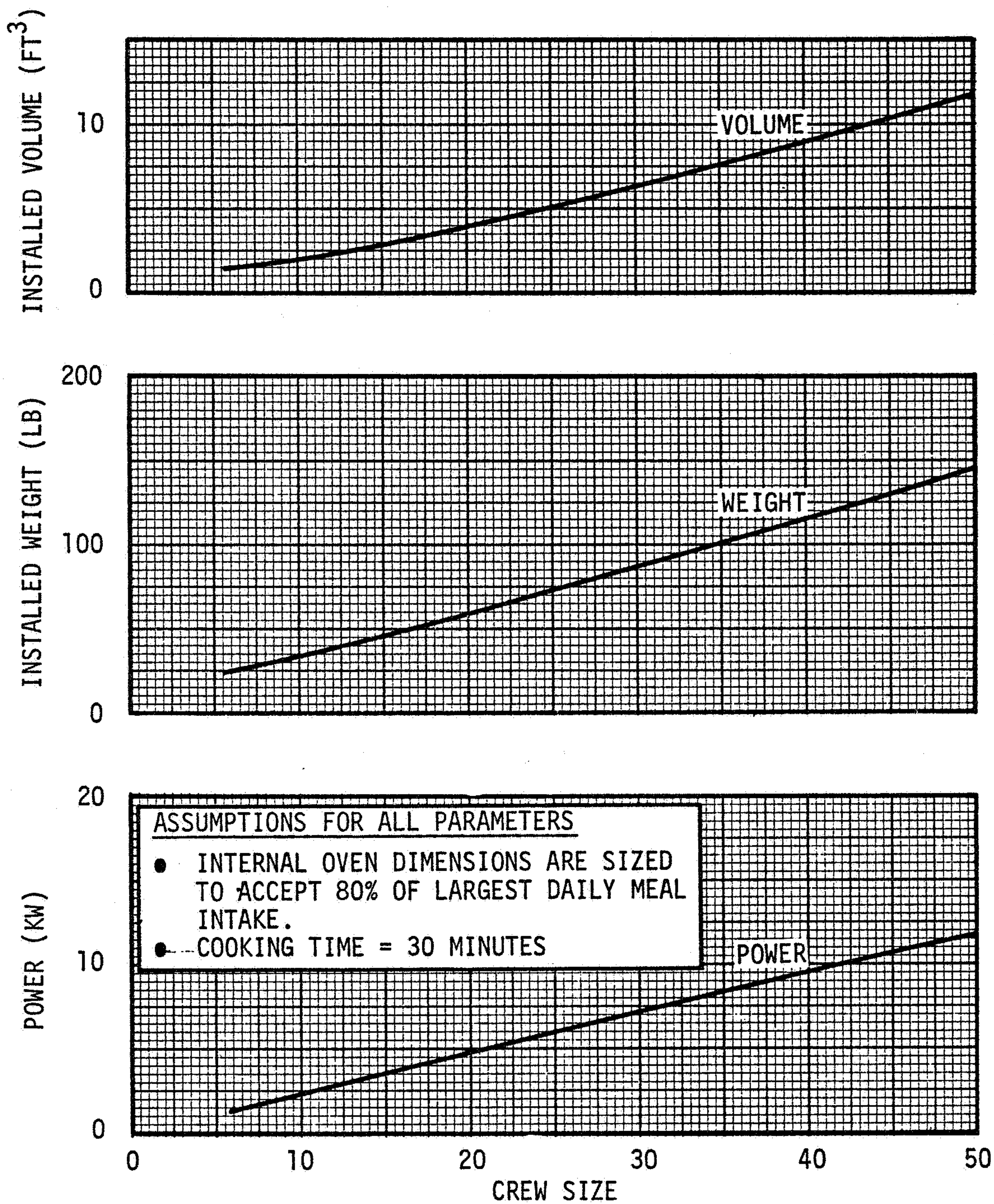


Figure 5-1. Hot Air Convection Heating Oven Parameters

Microwave Heating Oven

The microwave oven relies on a magnetron tube to generate high frequency energy necessary to penetrate and warm foods. The microwave is ducted from the generation region into the food heating compartment where a suitable frequency mixer is used to preclude hot spots in the food.

Engineering Data*

Food temperature

Frozen = -10°F
Prepared = 160°F

Installed volume vs crew size	Figure 5-2
Installed weight vs crew size	Figure 5-2
Power required vs crew size	Figure 5-2

Resistance Heating Oven

Electrically heated quartz elements radiate heat to the food cavity. The oven functions similar to a household broiling oven.

Engineering Data*

Food temperature

Frozen = -10°F
Prepared = 160°F

Installed volume vs crew size	Figure 5-3
Installed weight vs crew size	Figure 5-3
Power required vs crew size	Figure 5-3

*Sample calculations are presented in Appendix A.

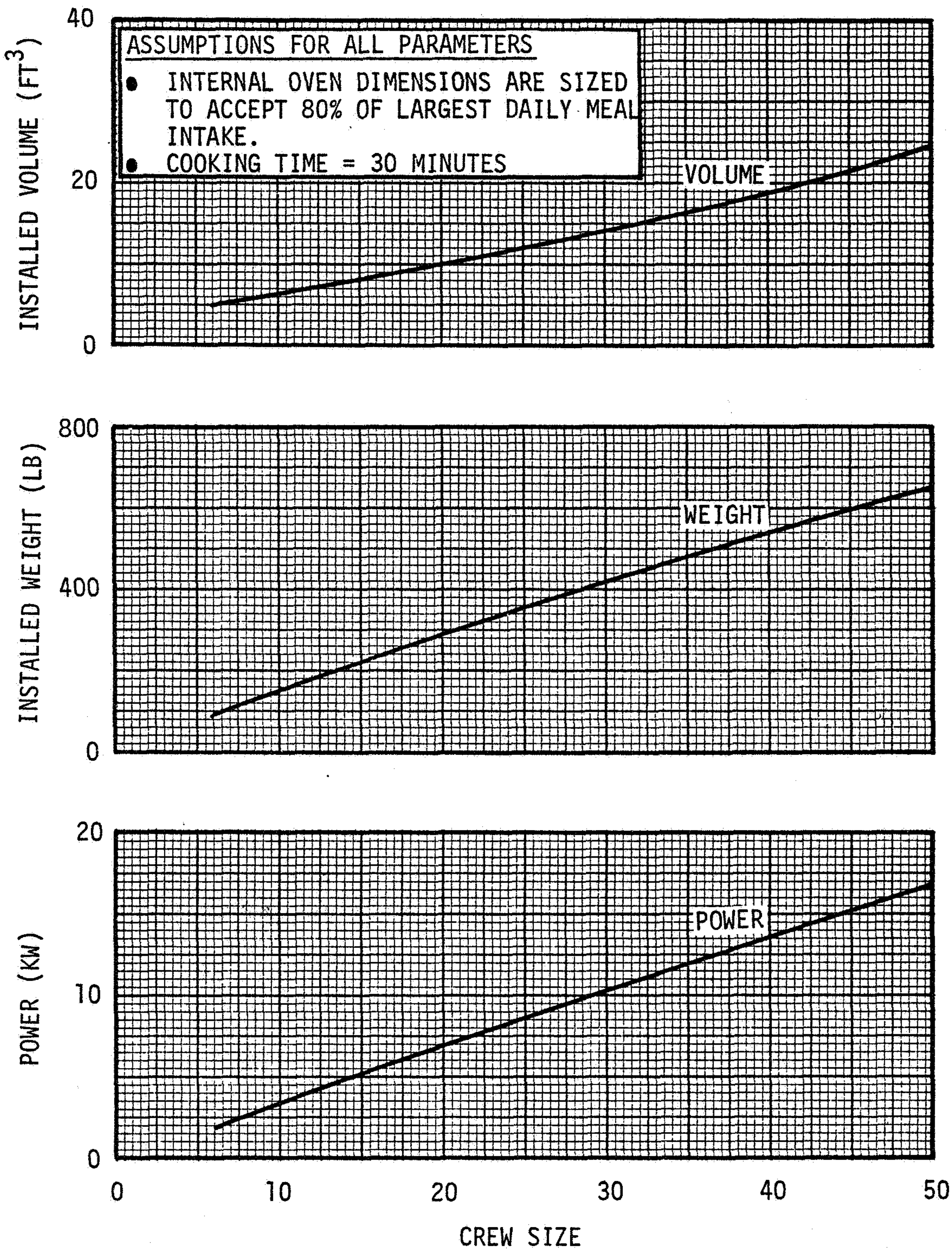


Figure 5-2. Microwave Heating Oven Parameters

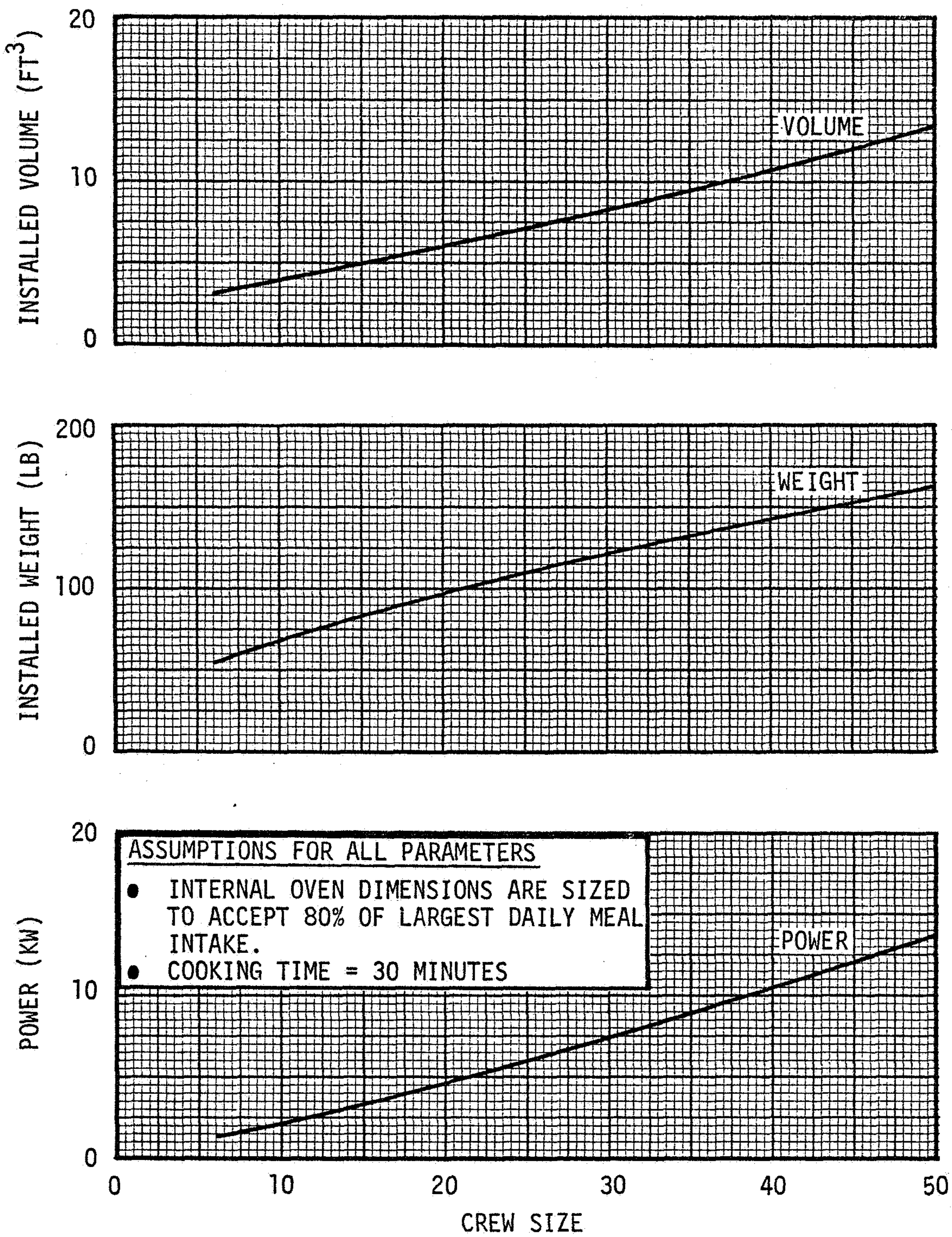


Figure 5-3. Resistance Heating Oven Parameters

Self-Heating Food Package

Resistance heating elements are imbedded or laminated into the food package. Electrical power is applied directly to the food packaging and the food package acts as an oven.

Engineering Data*

Food temperature

Frozen = -10°F
Prepared = 160°F

Installed volume vs crew size	Figure 5-4
Installed weight vs crew size	Figure 5-4
Power required vs crew size	Figure 5-4

Combination Microwave and Resistance Heating Oven

The microwave oven is fitted with quartz resistive heating elements. This combines the speed and effectiveness of the microwave oven with the capability to broil or brown foods.

Engineering Data

Food temperature

Frozen = -10°F
Prepared = 160°F

Installed volume vs crew size	Figure 5-5
Installed weight vs crew size	Figure 5-5
Power required vs crew size	Figure 5-5

*Sample calculations are presented in Appendix A.

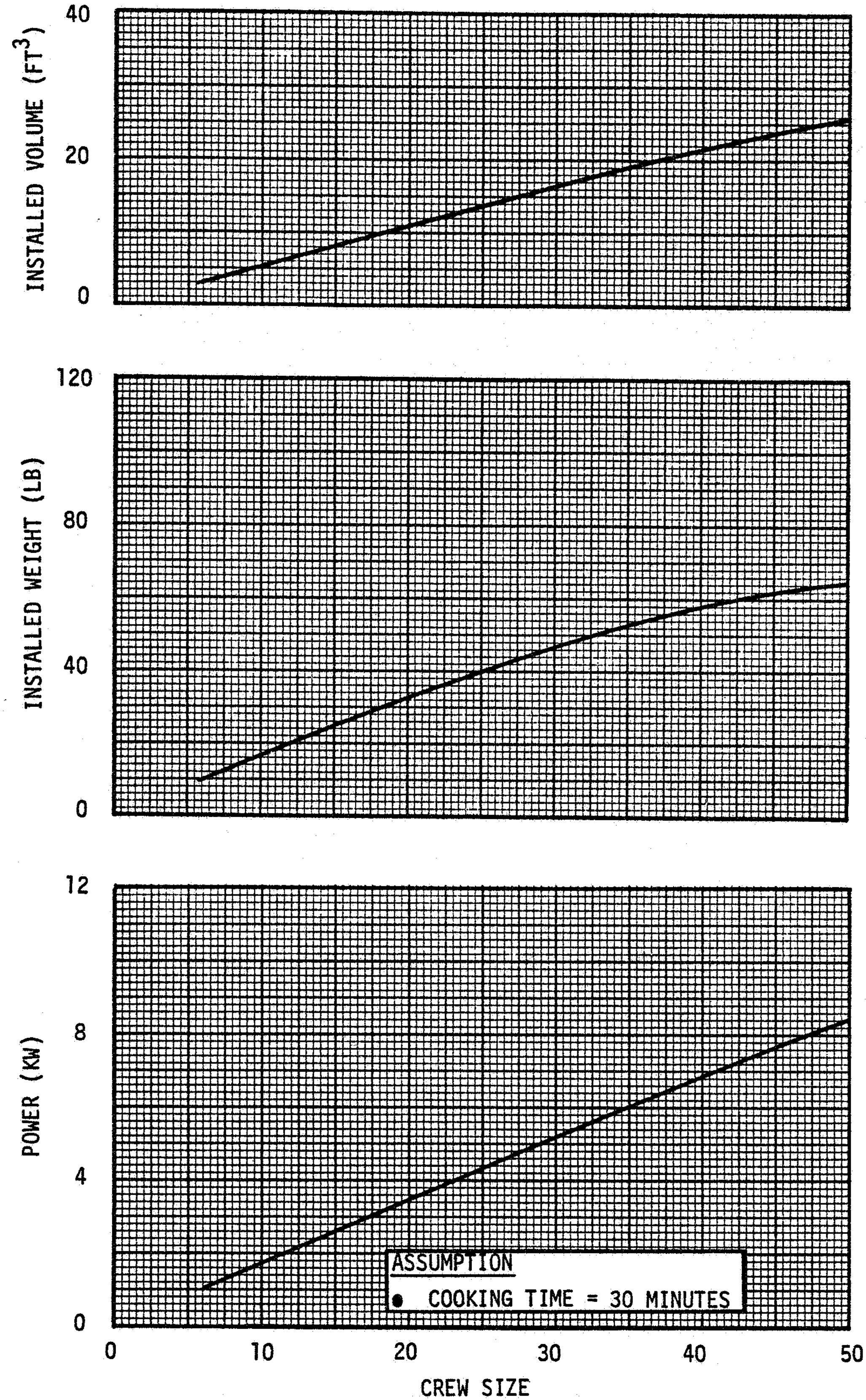


Figure 5-4. Self-Heating Food Package Parameters

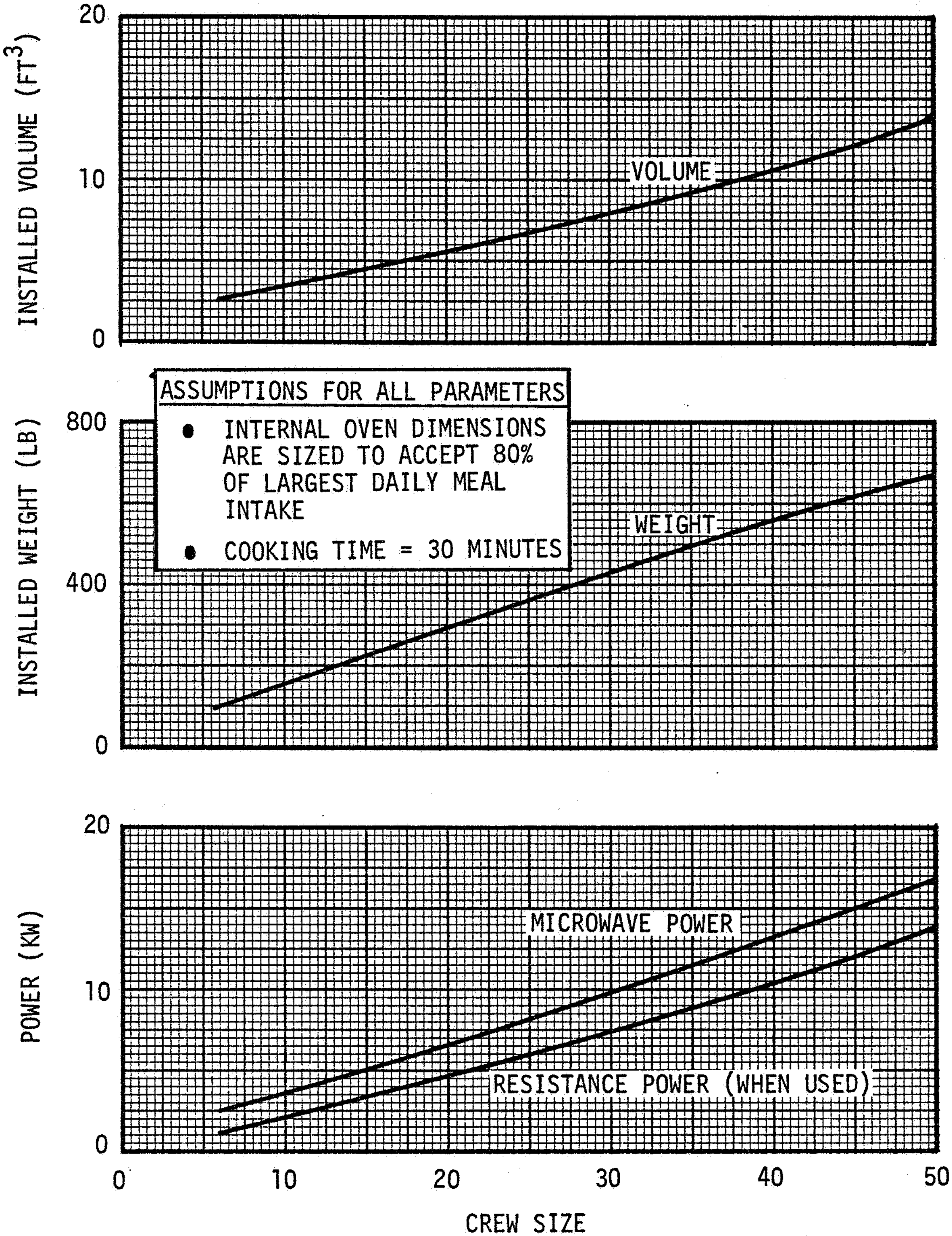


Figure 5-5. Combination Microwave and Resistance Heating Oven Parameters

Combination Hot Air Convection and Resistance Heating Oven

The hot air convection oven is fitted with quartz resistive heating elements. This combines the effectiveness of the hot air convective oven with the capability to broil or brown foods in the same oven.

<u>Engineering Data</u>

Food temperature

Frozen = -10°F
Prepared = 160°F

Installed volume vs crew size	Figure 5-6
Installed weight vs crew size	Figure 5-6
Power required vs crew size	Figure 5-6

Electrically Heated Food Tray

The food trays contain cavities which provide direct contact with the food containers. The food cavities are lined with resistance heating elements which provide conductive food heating and are equipped with individual heating controls.

<u>Engineering Data*</u>

Food temperature

Frozen = -10°F
Prepared = 160°F

Installed volume vs crew size	Figure 5-7
Installed weight vs crew size	Figure 5-7
Power required vs crew size	Figure 5-7

*Sample calculations are presented in Appendix A.

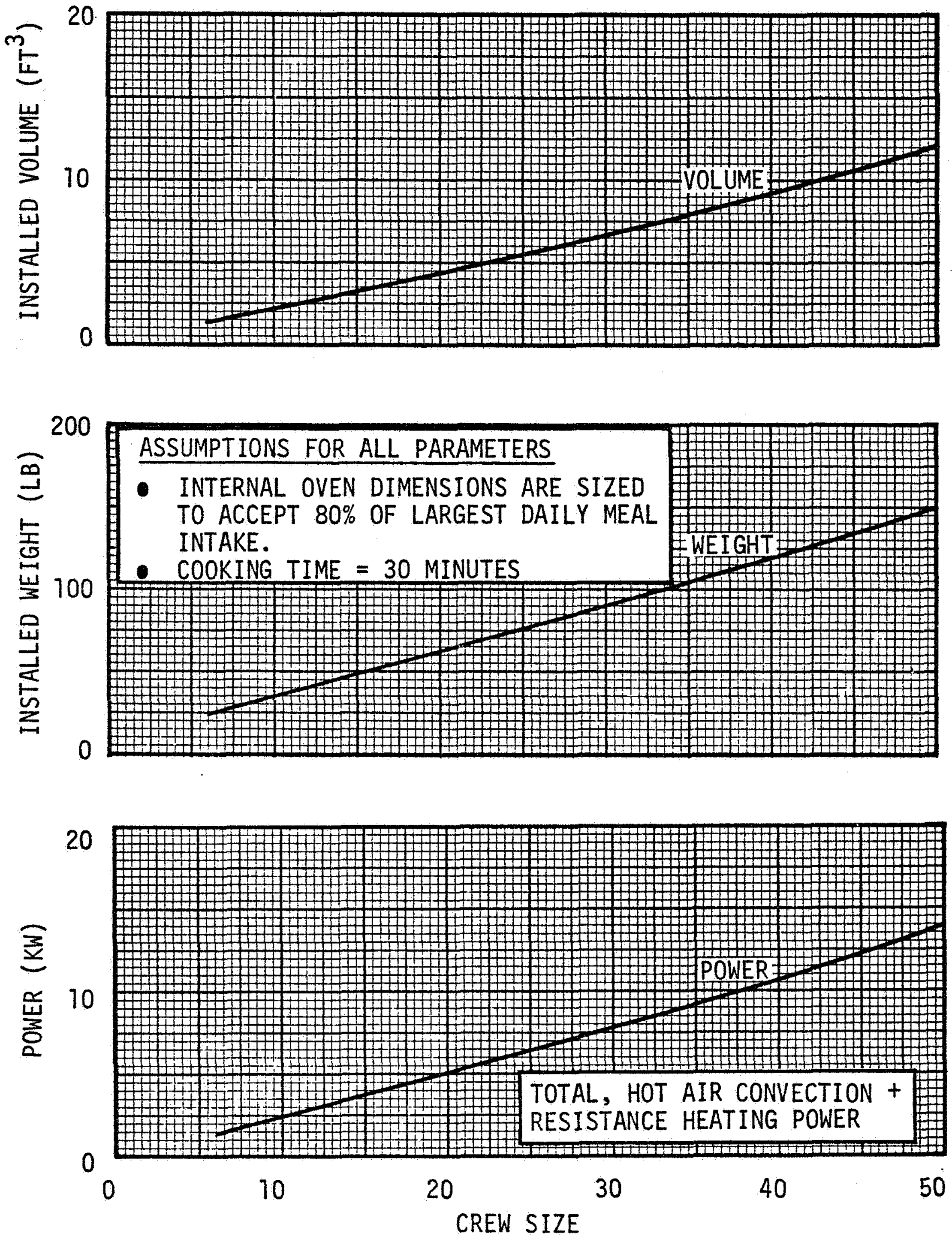


Figure 5-6. Combination Hot Air Convection and Resistance Heating Oven Parameters

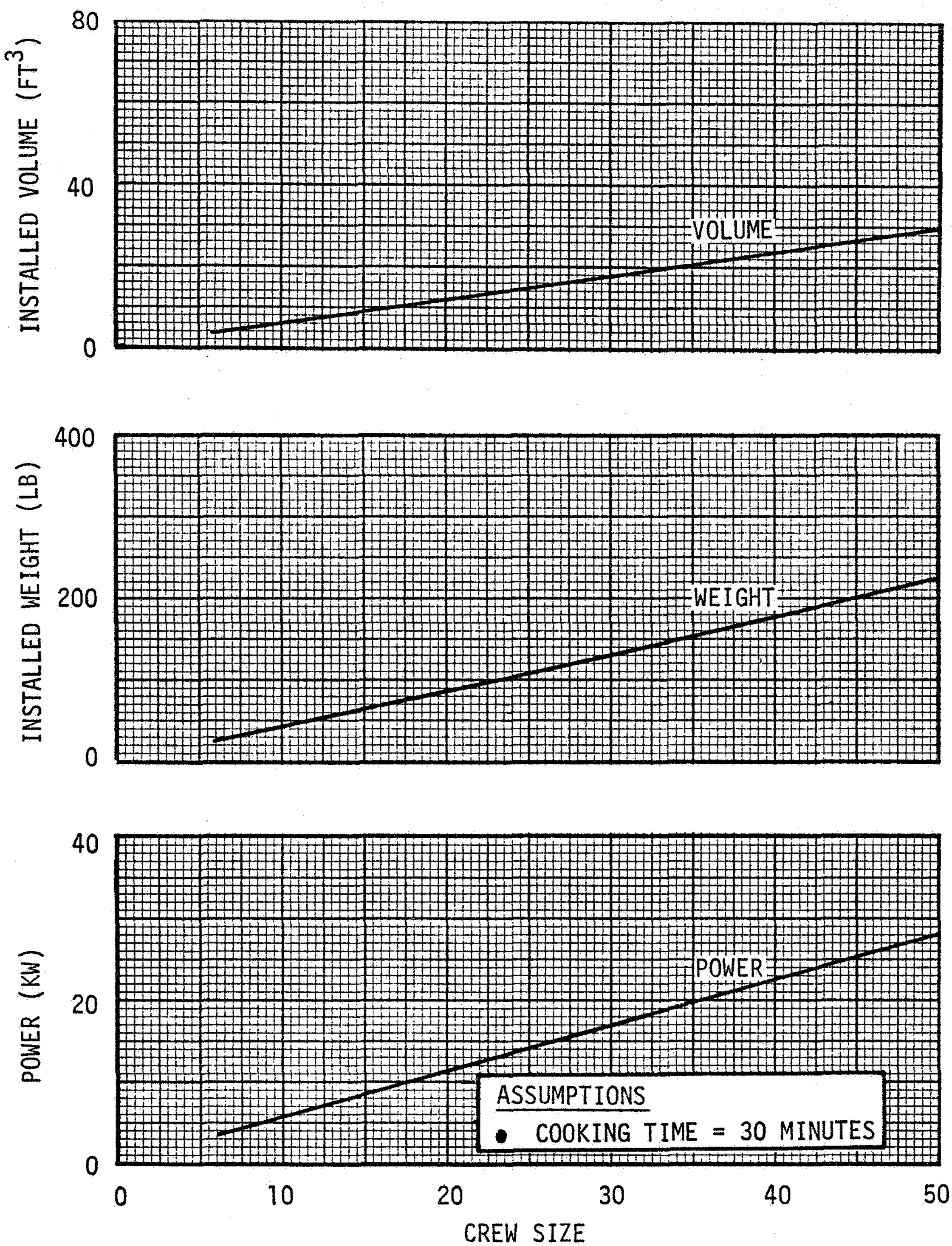


Figure 5-7. Electrically Heated Food Tray Parameters

5.3 PREPARATION UTENSIL CONCEPTS AND ENGINEERING DATA

The concepts discussed in this paragraph are: a) Mechanical Kneader, b) Hand-Operated Kneader, c) Hot Food Handling Tongs, d) Clam Shell Handling Device, e) Scoop, f) Shears, g) Hand-Operated Mixer Blender, h) Spatula, and i) Food Chopper.

Mechanical Kneader

This utensil is a hand-operated device which holds and mechanically kneads plastic type food packages. The kneading that blends or mixes dry foods or powder and liquids is accomplished by passing the food package between a series of rollers. The installed utensil weighs 1.2 pounds and occupies 0.01 cubic foot for a 12-man crew.

Hand-Operated Kneader

This is a technique-oriented concept requiring hand kneading by the crewman to accomplish the kneading.

Hot Food Handling Tongs

This utensil is a hand-held, hand-operated device which permits manual gripping. The self-adjusting tongs weigh 1.3 pounds and occupy 0.035 cubic foot for a 6 to 12-man crew.

Clam Shell Handling Device

This utensil is a hand-held, hand-operated clam shell type scoop and claw device which is capable of food retention and transfer. The utensil weighs 0.313 pound and occupies 0.005 cubic foot for a 6 to 12-man crew.

Ice Cream Type Scoop

The utensil is a hand-held, hand-operated device suitable for separation and distribution of bulk food to portion sizes. The device weighs 0.438 pound and occupies 0.030 cubic foot for a 12-man crew.

Kitchen Utility Shears

This utensil consists of a normally configured shears (scissors) and is utilized to open food packages. The shears are 5 inches long by 2 inches wide by 1/4 inch thick, weigh 0.25 pound, and occupy 0.001 cubic foot for a 6 to 12-man crew.

Hand-Operated Mixer Blender

This utensil is a cylindrically shaped container with a hand-operated trigger mechanism which activates an oscillating type mixing or blending action. The device is utilized to mix or blend ingredients for beverages, desserts, and soft foods. The utensil weighs 0.625 pound and occupies 0.038 cubic foot for a 12-man crew.

Spatula

This utensil is a hard rubber or plastic type material with a handle and wedge shaped blade for scraping, stirring, and mixing foods. The utensil weighs 0.188 pound and occupies 0.002 cubic foot for a 12-man crew.

Food Chopper

This utensil is a hand-actuated, four-bladed chopper enclosed in a see-through housing. The device is utilized for breaking and chopping foods. The utensil weighs 0.625 pound and occupies 0.076 cubic foot for a 12-man crew.

6.0 FOOD SERVING

The food serving concepts are designed to create an earth-like environment aboard the spacecraft. The basic concepts are self-service, steward service, and a mechanical delivery system. An additional approach is a variation of self-service where the crewman would assemble and consume his meal directly at a single point station, rather than transport food to a designated dining area.

Eating in Galley

The crewman will assemble his own meal onto a tray or heat a preassembled meal and consume the meal in the galley area itself, thus requiring no special serving equipment. Using this concept, each crewman will be responsible for preparing his own food and performing subsequent cleanup. The galley design will be specifically configured to accommodate this concept arrangement.

Steward Service

The prepared meals will be carried to the dining area by a steward who may also be the cook, depending on crew size. The steward will therefore be responsible for performing all galley, serving, and clean-up tasks.

Self-Serving

The crewmen will withdraw their own prepared meals from holding ovens or storage racks and individually transport them to the dining area with no special assistance equipment, other than the food tray or dish containing the food. The meals will be prepared either by a single designated crewman or by each individual crewman responsible for his own meal. Each crewman will be obligated to return his food tray or dishes to the galley area, where again, a designated crewman may be responsible for clean-up.

7.0 FOOD AND WATER CONSUMPTION PROVISIONS

7.1 NON-LIQUID CONTAINMENT CONCEPTS AND ENGINEERING DATA

The concepts discussed in this paragraph are: a) Pre-Cut, b) Cohesive, c) Edible Membrane Coating, d) Package Containment, e) Ribbed Surface Tray, and f) Recessed Surface Tray.

Pre-Cut Bite-Sized Components

The solid and semi-solid menu items (i.e., meats, large vegetables, breads, and cakes) will be prepared and placed on a tray as bite-sized items. This system will allow eating with fork or spoon only, leaving little possibility of spillage due to the impact of tangential forces while cutting or tearing apart.

All Cohesive Menu Components

The menu components will be covered with a viscose sauce or coating which imparts cohesive and adhesive properties. The viscose sauces can be made with or without taste. The adhesive qualities of the sauces allow easy consumption without the possibility of spills.

Edible Membranes Coating

The food on each tray section is covered with an edible coating. This coating is applied with a brush or specially designed spray prior to serving. The edible coating over the menu item allows transport and easy consumption of food with good heat and chill retention.

Package Containment

The menu items will be reconstituted and served in the packages. The packages will be fitted with a front opening tear flap for easy utensil access. This system represents no real improvement over existing Apollo feeding techniques.

Tray with Spiked or Ribbed Surface

The tray with spikes or nubs provides for more positive retention of food in the horizontal plane. It is constructed with or without recesses. This type of tray configuration might be more applicable to retention of menu items which require cutting, where tangential forces are applied. Ribbed surfaces present a potential contamination hazard if particular care is not taken to ensure all food debris has been removed.

Engineering Data

Tray constructed of polymide

Tray size = 14 in. x 14 in. x 1.5 in.

Tray thickness = 0.05 in.

Individual tray weight: 0.85 lb

Tray with Recessed Surface

The tray recesses are sized according to menu quantities such that packaged or unpackaged menu items can be kept separate and consumed from the tray. Cohesive foods tend to remain in place when in contact with a smooth formed surface. This tray lends itself to limited movement while food is in place, ease in cleaning due to smooth surfaces, and the establishment of familiar earth-like dining.

Engineering Data

Tray size = 14 in. x 14 in. x 1.5 in.

Thickness of tray = 0.05 in.

Weight per tray = 0.85 lb

7.2 LIQUID CONSUMPTION CONCEPTS

The concept discussed in this paragraph is the closed container.

Closed Containers

The liquid containers with covers are provided with straw placement provisions or configured to permit mouth withdrawal of contents through a lip port. The positive and negative pressure for liquid displaced must be considered.

Engineering Data

Rigid urethane collapsible shell

Density	= 0.051 lb/in^3
Thickness	= 0.031 in.

Itypaton rubber drink/filler valve

Density	=	$0.040\ lb/in^3$
Thickness	=	0.010 in.

Fluoro elastomer flexible liner

Density	=	$0.051\ lb/in^3$
Thickness	=	0.025 in.

Cup weight = 0.207 lb

Cup mass volume = $4.117\ in^3$

7.3 DINING UTENSIL CONCEPTS AND ENGINEERING DATA

The concepts discussed in this paragraph are: a) Reusable Utensils, b) Unconventional Utensils, and c) Disposable Utensils.

Reusable Utensils

The crewmen can utilize conventional knifes, forks, and spoons either individually or in combination with each other. The crew member could also utilize unconventional utensils described as follows:

- Spork: A combination spoon-fork, i.e., tines on the end of a spoon.
- Combination knife/fork/tong: hand-held, hand-operated tong integrated on a knife edge, one flat edge, and opposing prong ends.

Engineering Data

Conventional Utensils

Utensil size	=	3/4 standard size
Spoon weight (each)	=	0.050 lb
Spoon volume (six)	=	$0.021\ ft^3$
Knife weight (each)	=	0.106 lb
Knife volume (six)	=	$0.004\ ft^3$
Fork weight (each)	=	0.070 lb
Fork volume (six)	=	$0.021\ ft^3$

Unconventional Utensils

Spork size	=	3/4 standard spoon
Spork weight (each)	=	0.046 lb
Spork volume (six)	=	0.021 ft^3
Combination knife/fork/tong (each)	=	8.5 in. (L) x 1.0 in. (W) x 1.25 in. (H)
Knife/fork/tong weight (each)	=	0.102 lb
Knife/fork/tong volume (six)	=	0.036 ft^3

Disposable Utensil

The crewmen will utilize disposable utensils similar to the reusable utensils discussed previously, e.g., disposable knife, fork, spoon, spork and combination knife/fork/tong.

7.4 MAN RESTRAINTS

Refer to Volume 1, Mobility and Restraint, for personnel restraint concepts and engineering data.

8.0 FOOD CLEANUP

Food cleanup techniques are applicable to the galley and dining facilities within a spacecraft. This section is limited in scope to general purpose wipes, wipe dispensers, soiled wipe stowage, utensil washing and vacuum cleaning techniques.

8.1 SANITARY WIPE CONCEPTS AND ENGINEERING DATA

The concepts discussed in this paragraph are the reusable and disposable wipes.

Reusable Galley/Dining Area Wipes

Impregnated reusable wipes offer a simple means of washing and sanitizing work counters, food preparation equipment, tables, or general confines of galley and dining areas. The utility handwipe will be impregnated or dampened periodically during use with a premixed evaporative detergent/germicidal solution.

Engineering Data

Wipe size unfolded	=	12 in. x 12 in.
Wipe size folded	=	6 in. x 3 in. x 0.16 in.
Wipe weight (each)	=	0.075 lb
Wipe volume folded (each)	=	0.001672 ft^3

Disposable Galley/Dining Area Wipes

Usage of disposable hand wipes will be identical to usage of the reusable wipes. The disposable wipes could be paper towels impregnated or saturated with a solution of benzalkonium chloride, chlorothymol, propylene glycol, and alcohol.

Engineering Data

Wipe size packet (each)	=	2.25 in. x 3.0 in. x 0.125 in.
Wipe weight packet (each)	=	0.013 lb
Wipe volume packet (each)	=	4.884×10^{-4} ft^3
Daily usage	=	2 to 3 per man-day

Disposable/Reusable Personal Wipes

Refer to Volume 6, Personal Hygiene, for personal wipe concepts and engineering data.

8.2 WIPE DISPENSER CONCEPTS AND ENGINEERING DATA

The dispenser concepts discussed in this paragraph are for the reusable and disposable galley/dining area wipes.

Reusable Wipe Dispenser

The dispenser is a simple "box-like" open container with suitable wipe retention provisions.

Engineering Data

Assume: 2 dispensers for 12-man crew

Dispenser size (each)	=	13 in. x 13 in. x 5 in.
Dispenser weight (each)	=	5.0 lb
Dispenser volume (each)	=	0.489 ft^3

Disposable Wipe Dispenser

The dispenser is similar to the commercial units (automatic self-advancing feed type) with suitable wipe retention provisions.

Engineering Data

Assume: 2 dispensers for 12-man crew

Dispenser size (each)	=	5 in. x 5 in. x 12 in.
Dispenser weight (each)	=	3.0 lb
Dispenser volume (each)	=	0.174 ft^3

8.3 SOILED WIPE STOWAGE CONCEPTS AND ENGINEERING DATA

The concepts discussed in this paragraph are for temporary stowage of soiled wipes and debris.

Temporary Stowage of Reusable Soiled Wipes

The storage unit is a simple container which has a cloth bag liner, such as a commonly used laundry bag, for zero-g retention of a daily quantity of soiled reusable wipes. The cloth bag liner can be laundered along with its contents, and continually reused until deteriorated.

Engineering Data

Assume: • 1 container for 6 to 12-man crew

• 1 bag per container per day

Container size	=	10 in. x 10 in. x 30 in.
Container weight	=	2.0 lb
Container volume	=	1.736 ft^3
Bag size (folded)	=	5 in. x 10 in. x 0.5 in.
Bag weight	=	0.2 lb
Bag volume (folded)	=	0.01446 ft^3

Temporary Stowage of Debris and Waste Foods

The storage unit is a simple container which has an impervious disposable liner (such as a common garbage bag) for retention of debris generated in the galley and dining areas. The unit is applicable to the food system in providing a means for storing collected debris (e.g., food wraps, waste food, soiled disposable wipes, disposable utensils) resulting from food preparation, dining, and various cleaning functions.

Engineering Data

Assume: • 1 container for 6 to 12-man crew

• 1 bag per container per meal

Container size	=	10 in. x 10 in. x 30 in.
Container weight	=	2.0 lb
Container volume	=	1.736 ft^3
Disposable bag size - folded (each)	=	5 in. x 10 in. x 0.1 in.
Disposable bag weight (each)	=	0.02 lb
Disposable bag volume (each)	=	0.00289 ft^3

8.4 UTENSIL WASHING CONCEPTS AND ENGINEERING DATA

The concepts discussed in this paragraph are the Automatic Dishwasher/Dryer and the Galley Sink/Hand and Utensil Washer.

Automatic Dishwasher/Dryer

The dishwasher/dryer is a specially developed unit, suitable for use in a zero-g environment aboard a spacecraft. The unit is applicable to the food system in providing a means for automatic cleansing and sanitizing of soiled food preparation devices, meal trays, cups and dining utensils. Interface is required with spacecraft electrical power system, structural design, and water system.

Engineering Data

Assume washing of the following utensils for a 12 man crew.

- 12 trays, each of which is 14.0 in. x 14.0 in. x 1.5 in.
- 12 drinking cups, each of which has a 3.0 in. diameter and is 4.5 in. tall.
- 36 utensils, consisting of 12 sets of knives, forks, and spoons, each set is approximately 7.0 in. x 1.5 in. x 1.0 in.
- Miscellaneous food preparation devices for which 25 percent volume allowance is allocated.

Washing cavity	=	16 in. x 20 in. x 30 in.
Washing volume	=	5.555 ft^3
Unit weight	=	180 lb
Unit volume	=	18.0 ft^3
Average power	=	19,500 watt-hr/day

Galley Sink Hand/Utensil Washer

This unit has a chamber large enough to enable insertion of utensils up to the size of a small food tray. The galley sink is applicable to the food system in providing a means for washing hands prior to, during, and subsequent to food handling, and for infrequent washing of some utensils. Interface is required with the spacecraft electrical power system, structural design, and water system.

Engineering Data

Assume: Unit used for 12-man crew

Unit size	=	24 in. x 24 in. x 40 in.
Unit weight	=	60.0 lb
Unit volume	=	13.3 ft^3
Average power	=	1200 watt-hr/day

8.5 VACUUM CLEANUP TECHNIQUES

Refer to Volume 3, Housekeeping, for a discussion on vacuum cleanup.

APPENDIX A

SUPPORTING ENGINEERING DATA AND ANALYSIS

APPENDIX A CONTENTS

APPENDIX A CONTENTS (CONCLUDED)

A.1 SPACE RADIATOR REFRIGERATOR/FREEZER ANALYSIS

The space radiator cooling configuration within the locker consists of an aluminum sheet structure and a circuit of continuous coolant tubes. The aluminum sheets isolate the frozen food from the inner surface of the foam-insulation walls of the locker. The coolant tubes are integral with these sheets. Heat leaking through the foam walls is intercepted by the aluminum sheets while the coolant flowing through the tubes collects the heat and directs it away from the freezer locker.

The space radiator located on the outer surface of the vehicle receives the warm coolant fluid and extracts heat from it. The fluid is then recirculated back into the cooling circuit within the locker. One or more space radiators may be required if the vehicle lacks attitude control with respect to the sun; the coolant would automatically be routed to the proper radiator using diverter valves to accomplish the switching. Because the coolant flow rates are so small, the coolant pump charges a pressurized accumulator once every 4-hour cycle.

A.1.1 Thermal Analysis of Food Locker (Freezer or Refrigerator).

A.1.1.1 Food Locker Assumptions (Figure A-1).

- Volume of food in freezer locker = 100 ft^3
- 4-inch polyurethane foam insulation is used in all external walls and doors.
- 1- and 2-inch spacing allowed between compartments for packaging, structure, insulation, finger clearance.

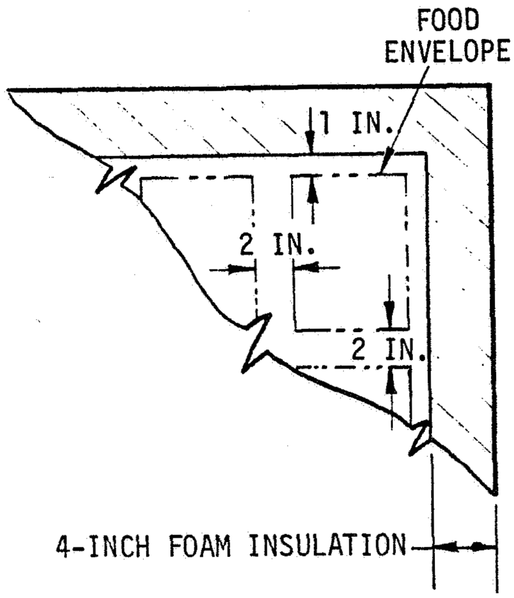


Figure A-1a. Food Locker Dimensions

- The foam envelope enclosing the frozen food will remain cubical in shape to minimize surface area losses; this rationale is valid only to the extent that the width does not exceed 40 inches or the height does not exceed 76 inches. A total width of 40 inches will permit a crewmember to span 36 inches to food packages at the rear of the freezer compartment. A total height of 76 inches will facilitate the installation of the freezer unit within the deck-to-deck dimension. The total heat losses associated with the frozen food locker are:

  a) Surface area loss
  b) Door seal loss
  c) Conduction (structural) loss
  d) Door opening loss.

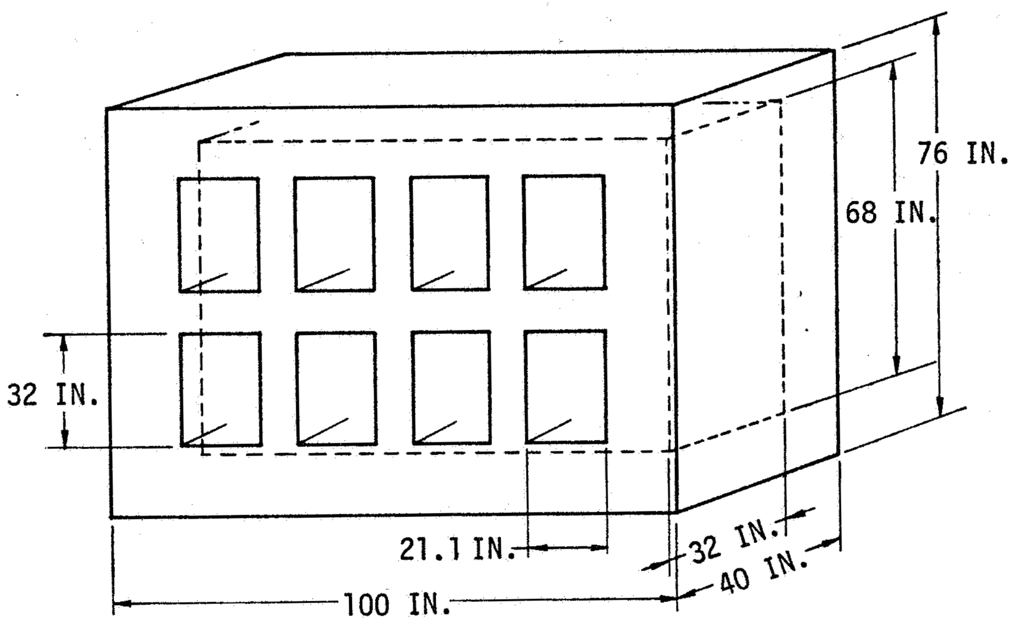


Figure A-1b. Food Locker Dimensions

A.1.1.2 Analysis of Freezer Wall Surfaces.

A.1.1.2.1 Freezer Wall Assumptions (Figure A-2).

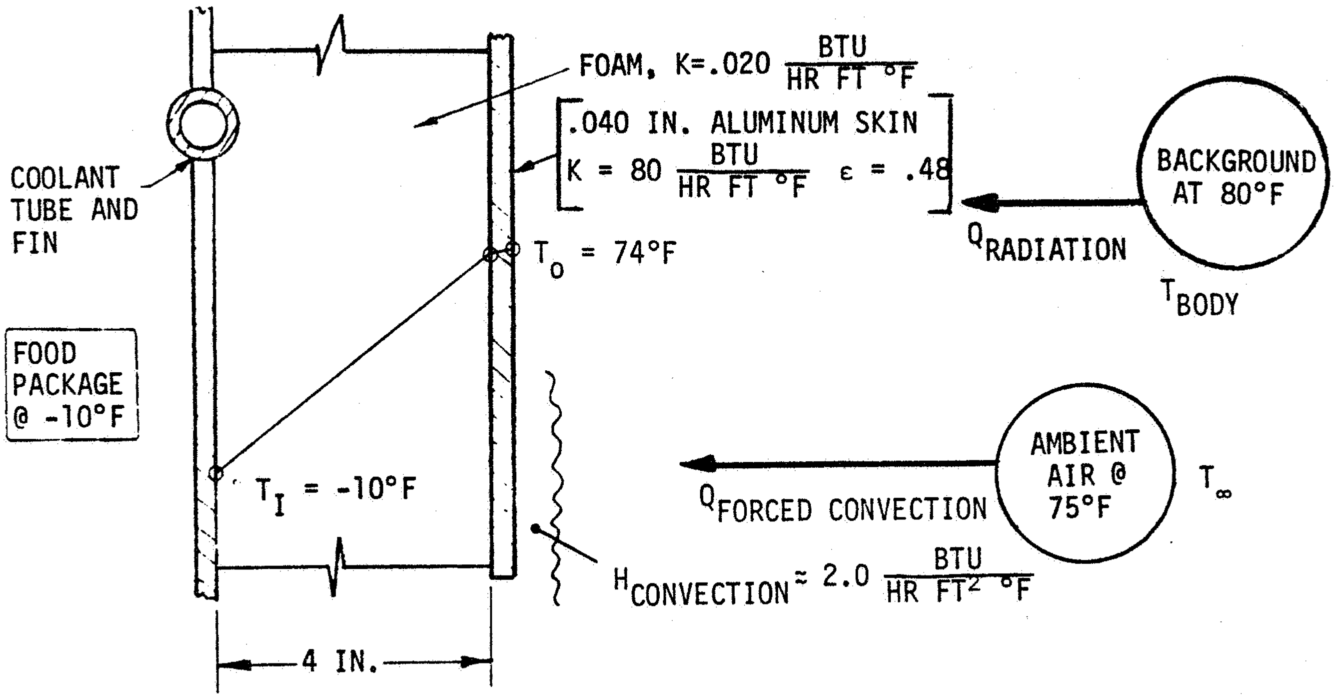


Figure A-2. Freezer Wall Parameters

A.1.1.2.2 Convective Losses.

$$Q_{convection} = hA(T_\infty - T_o) = 2.0(1.0)\ (75 - 74)$$

$$= 2.00 \text{ Btu/hr}$$

A.1.1.2.3 Radiation Losses.

$$Q_{radiation} = \varepsilon A[\delta T^4_{body} - \delta T_o{}^4] = .48(1.0)\ [145.7 - 139.3]$$

$$= 3.04 \text{ Btu/hr}$$

A.1.1.2.4 Summary Losses and Check.

$$Q_{total} = Q_{convection} + Q_{radiation}$$
$$= 2.00 \text{ Btu/hr} + 3.04 \text{ Btu/hr}$$
$$= 5.04 \text{ Btu/hr}$$

Check -

$$Q_{insulation} = UA(T_o - T_i)$$

where

$$\underset{T_o \rightarrow T_i}{\underset{\text{overall}}{U}} = \frac{1}{\frac{\Delta X}{K} + \frac{\Delta X}{K}}$$

$$= \frac{1}{\frac{.040/12}{80} + \frac{4.0/12}{.020}}$$

$$U = 0.06 \frac{\text{Btu}}{\text{hr-ft}^2\text{-°F}}$$

$$Q_{insulation} = UA\ (T_o - T_i) = 0.06(1.0)\ (74 + 10)$$

$$= 5.04 \frac{\text{Btu}}{\text{hr}} \text{ per ft}^2 \text{ of freezer wall}$$

A.1.1.2.5 Example Surface Area Losses. Because the surface losses depend on both radiation and forced convection mechanisms operating upon the external locker surfaces, the exact loss through the walls depends upon the particular installation of the freezer locker within the vehicle. That is, if a freezer wall is butted against a deck or bulkhead, the radiation mechanism associated with that wall may vary unpredictably while the convection mechanism may drop to zero, altogether. To account for this, it is assumed that no heat leaks exist in the rear wall of the freezer locker. For the case of the 100 ft^3 food locker:

$$\text{Effective loss area} = 2(40 \times 76) + 2(40 \times 100) + (76 \times 100)$$
$$= 21{,}680 \text{ in}^2 = 150 \text{ ft}^2$$

$$\text{Surface area loss} = (150)\ 5.04 = 756 \text{ Btu/hr}$$

A.1.1.3 Analysis of Door Seal Losses.

A.1.1.3.1 Door Seal Assumptions (Figure A-3).

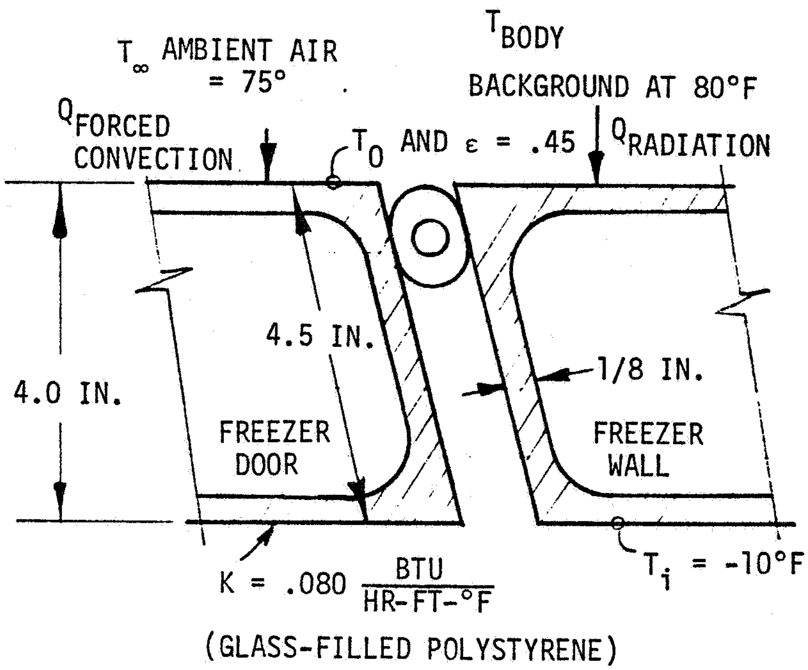


Figure A-3. Door Seal Parameters

A.1.1.3.2 Forced Convection Losses.

$$Q_{forced\ convection} = hA(T_\infty - T_o)$$

$$h \approx 2.0 \frac{Btu}{hr\text{-}ft\text{-}°F}$$

$$A \equiv 2(.125/12 \times L)\ ft^2$$

$$T_\infty = 75°F$$

A.1.1.3.3 Radiation Losses.

$$Q_{radiation} = \varepsilon A \left[\delta T^4_{body} - \delta T_o{}^4\right]$$

$$\varepsilon = .45$$

$$A \equiv 2(.125 \times L)\ in.ft$$

$$T_{body} = 80°F$$

A.1.1.3.4 Seal Convection Losses.

$$Q_{seal\ convection} = \frac{KA}{\Delta X}(T_o - T_i)$$

$$K = .080 \frac{Btu}{hr\text{-}ft^2\text{-}°F}$$

$$A \equiv 2(.125 \times L) \text{ in. ft}$$

$$\Delta X = 4.50 \text{ in.}$$

$$T_o = -10°F$$

A.1.1.3.5 Door Seal Analysis Summary.

Assume $T_o = 69°F$

$Q_{radiation} = .00936(L)\ [145.7 - 134.22] = 0.108$ Btu/hr

$Q_{convection} = .04165(L)\ (75 - 69) \quad = 0.250$ Btu/hr

where $Q_{total} \quad = 0.358$ Btu/hr

$Q_{seal\ conduction} = .00445(L)\ (69 + 10) \quad = 0.351$ Btu/hr

$\therefore \quad Q_{radiation} + Q_{convection} = Q_{conduction}$

So that $T_o = 69°F$ and

$Q_{door\ seal\ losses} = 0.351(L)$

where L is length of door seal circumference in feet.

A.1.1.3.6 Example Door Seal Losses.

Circumference of door seals $= \frac{8}{12}(32 + 21.1)\ 2 = 70.8$ ft

Door seal loss = (70.8) .351 = 24.9 Btu/hr

A.1.1.4 Example Structural Conduction Losses. Assume structural conduction losses can be designed not to exceed 6% of surface and seal losses.

Loss = 0.06(756 + 24.9) = 47 Btu/hr

A.1.1.5 Example Door Opening Losses. Door opening losses rarely exceed 4 percent of total heat rate loss. A loss based on 4.5% will be assumed.

$$\text{Loss} = .045(828) = 37.3 \text{ Btu/hr}$$

A.1.1.6 Example Total Heat Losses. Figure A-4 gives the total heat losses versus food capacity retained in freezers or refrigerators.

$$Q_{total} = \text{Surface Area} + \text{Door Seal} + \text{Structural} + \text{Door Opening}$$

∴ total heat loss leaking into freezer interior (for the freezer containing 100 ft^3 of food) is:

$$756.0 + 24.9 + 47.0 + 37.3 = 865 \text{ Btu/hr}$$

Figure A-4 gives the total heat losses versus food capacity retained in freezers or refrigerators.

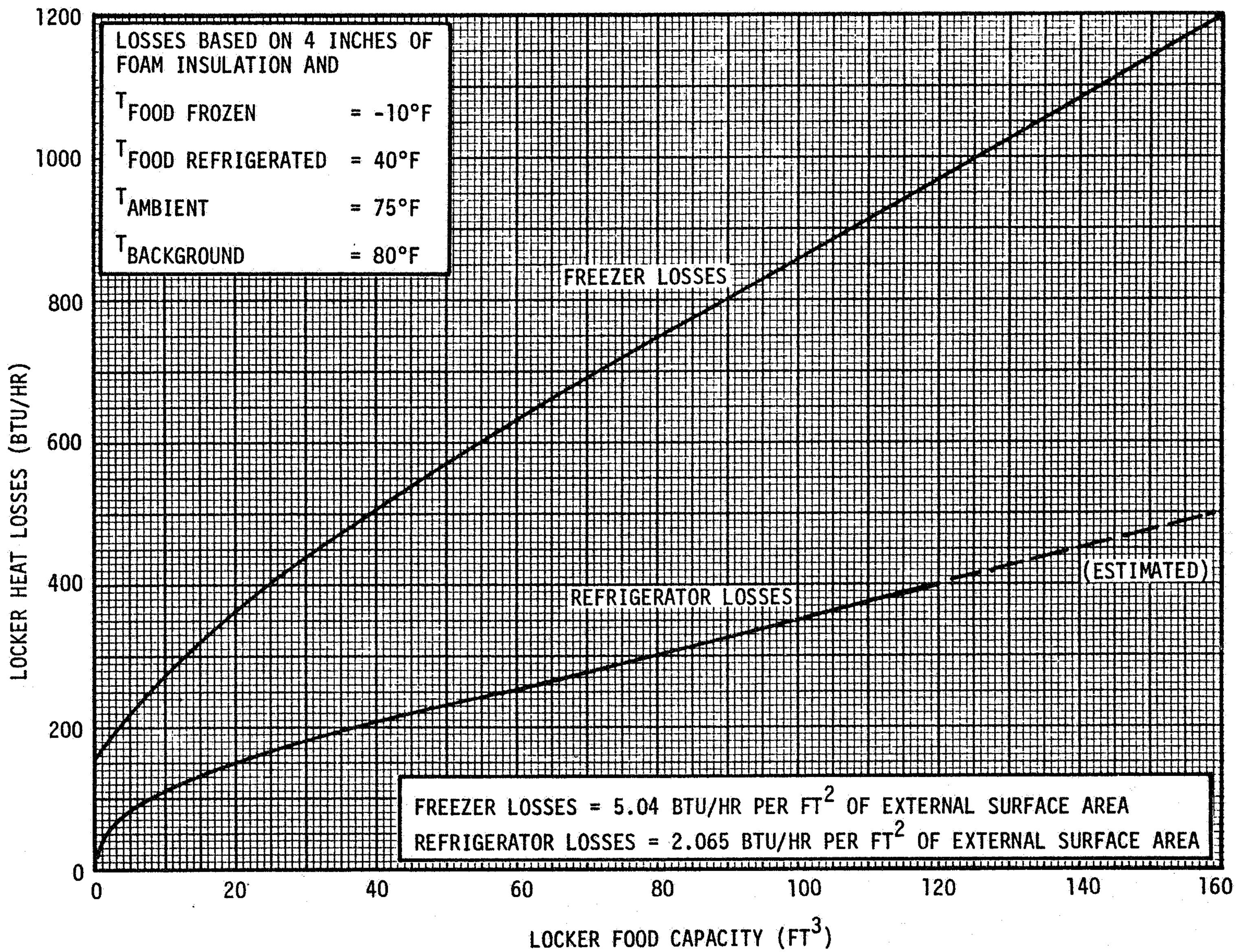
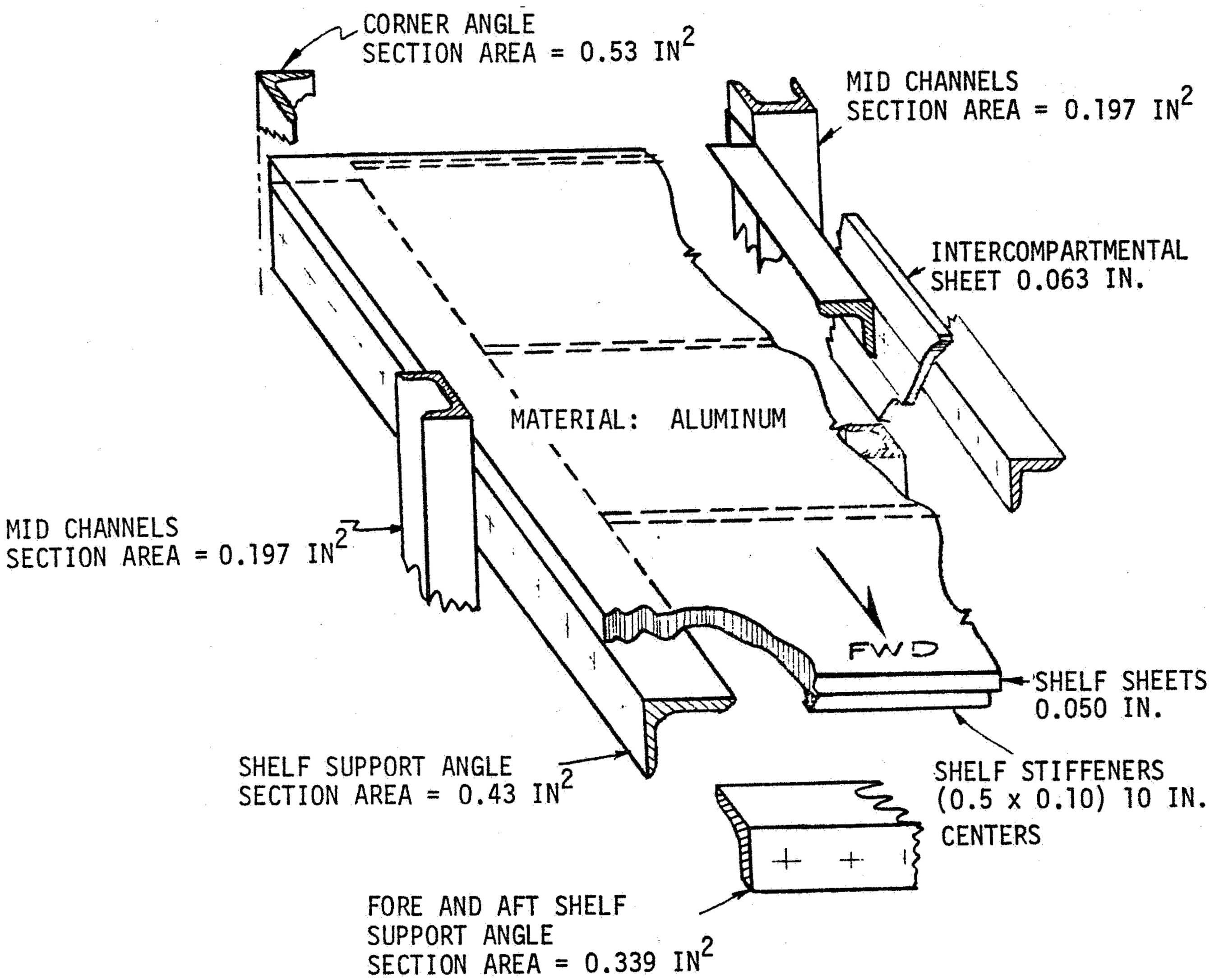


Figure A-4. Space Radiator Locker Heat Losses for Various Capacities

A.1.2 Structural Analysis of Food Locker (Freezer or Refrigerator).

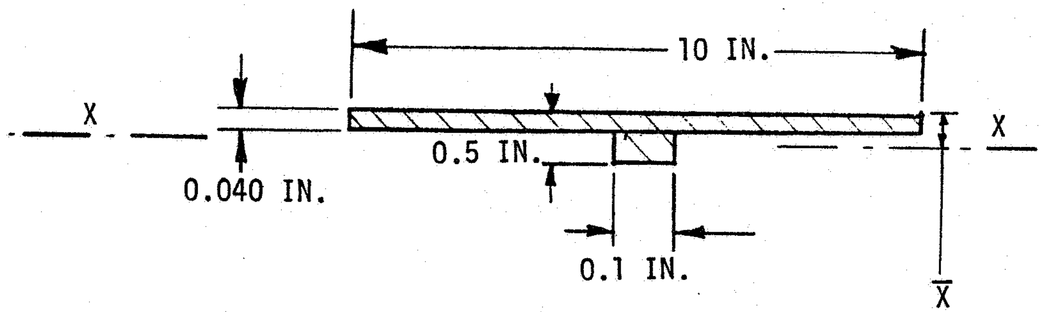
A.1.2.1 Typical Food Shelf Structure (Figure A-5).



Shown: Typical structural support of food shelves (100 ft^3 capacity). Retention devices and insulation are not shown.

Figure A-5. Food Locker Shelf Parameters

A.1.2.2 Shelf Sheet and Stiffener (Figure A-6).



$$\bar{X} = \frac{.5(.10)\ (.29) + 10(.04)\ (.02)}{.5(.10) + 10(.04)} = 0.272 \text{ in.}$$

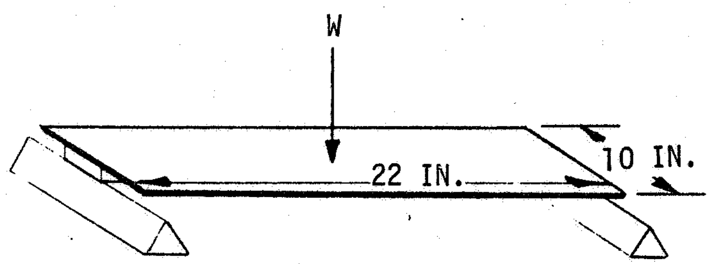
$$I_{XX} = 1/12(.10)\ (.5)^3 + .05(.018)^2 + 1/12\ (10)\ (.040)^3 + .40(.252)^2$$

Deflection of Shelf Sheets

$$\delta = \frac{5W\ell^3}{384\ EI}$$

$$= \frac{5(208.2)\ (22)^3}{384(10.7 \times 10^6)\ .0265}$$

$$\delta = 0.01016 \text{ inch}$$



$$W = \frac{\text{Food Weight}}{\text{Number Shelves}} \times \frac{\text{Shelves}}{\text{Sheets}}$$

$$W = \frac{5000}{8} \times \frac{1}{3}$$

$$W = 208.2 \text{ lb/sheet}$$

Stress in Shelf Sheets

$$\sigma = \frac{Mc}{I} = \frac{W\ell}{4}\ \frac{C}{I} = \frac{208.2}{4}\ (22)\ \frac{.272}{.0265}$$

$$\sigma = 11{,}900 \text{ psi}$$

$$(\text{F.S.} = \frac{53}{11.9} = 4.45)$$

Figure A-6. Shelf Sheet and Stiffener Parameters

A.1.2.3 Weight of Structural Members.

Shelf Support Angles

Wt = (area) (length) ρ = (.43) (36) (.10) 16 = 24.80 lb

Shelf Sheets and Stiffeners

(sheet)	Wt = (32 x 23) .050 (.10) 8	=	29.40 lb
(stiffener)	Wt = (.50 x .10) 19.0 (.10) 32	=	3.04 lb
	Total:		32.44 lb

Vertical Supports

(corner angles)	Wt = (area) length ρ = (.53) (76) (.10) 4	=	16.10 lb
(mid-channels)	Wt = (.197) (76) (.10) 11	=	16.50 lb
	Total:		32.60 lb

Intercompartmental Sheets

Wt = (72 x 36) (.063) (.10) 3 = 48.90 lb

Fore and Aft Support Angles

Wt = (area) (length) ρ = (.339) (100.) (.10) 4 = 13.60 lb

Structural Support Required for Vehicle Installation/Integration

Assume ~ 25% of structural weight of locker.

Wt = 0.25 (24.80 + 32.44 + 32.60 + 48.90 + 13.60)

Wt = 0.25 (152.3) = 38.10 lb

Total Structural Weight

Wt = (24.80 + 32.44 + 32.60 + 48.90 + 13.60 + 38.10)

Wt = 190.44 lb

A.1.2.4 Food Locker Weight Summary. Figure A-7 gives the total weight of the food locker versus the capacity of the locker. The capacity is based on volume of packaged food.

Weight of External Sheets

External Area - (40 x 76) 2 + (100 x 76) 2 + (100 x 40) 2 = 29,280 in^2

Weight = (area) (thickness) (density)
(29,280) (.030) (.10) = 87.84 lb

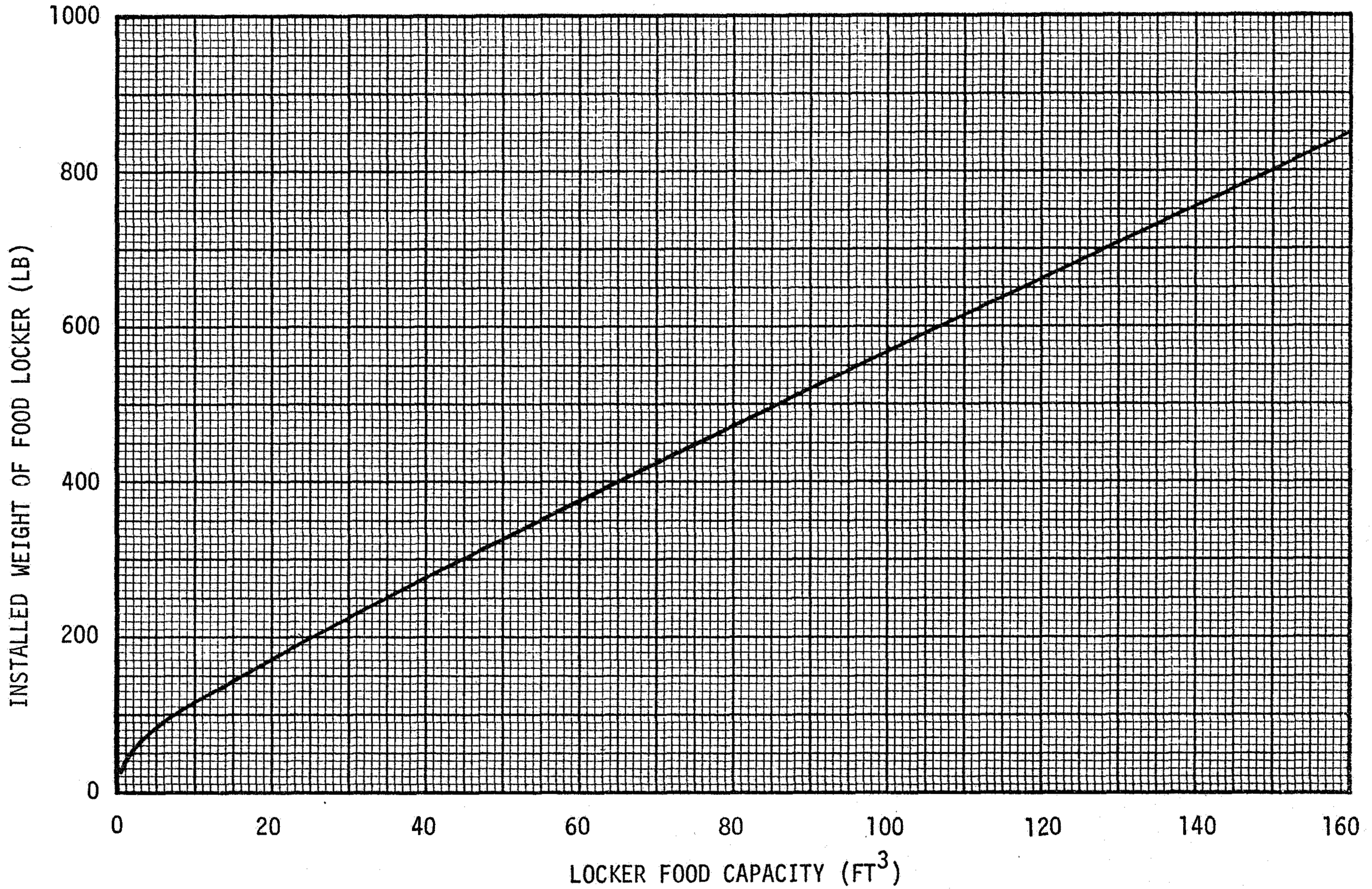


Figure A-7. Space Radiator Locker Weights for Various Food Capacities

Weight of Internal (Fin) Sheets

Internal Area = (92 x 32) 2 + (92 x 68) 2 + (100 x 40) 2 = 22,720 in^2

Weight = (area) (thickness) (density)
(22,720) (.050) (.10) = 113.50 lb

Weight of Foam Insulation

Weight = (area) (thickness) (density)

$$= \left(\text{internal area} + 16\left\{ L_o + W_i + H_i \right\}\right) \frac{4}{1728} (3.0)$$

$$= \left(22{,}720 + 16 \left\{100 + 92 + 68\right\}\right) \frac{4}{1728} (3.0) = 186.50 \text{ lb}$$

Structural Support (see Paragraph A.1.2.3)

Weight = 190.44 lb

Total Weight of (100 ft^3) Locker = 588.28 lb

A.1.3 Volume Analysis of Food Locker. Figure A-9 gives total volume of food locker shown in Figure A-8 versus food capacity.

- Food capacity = 100 ft^3
- Installed volume = 100 in. x 40 in. x 76 in. = 304,000 in^3

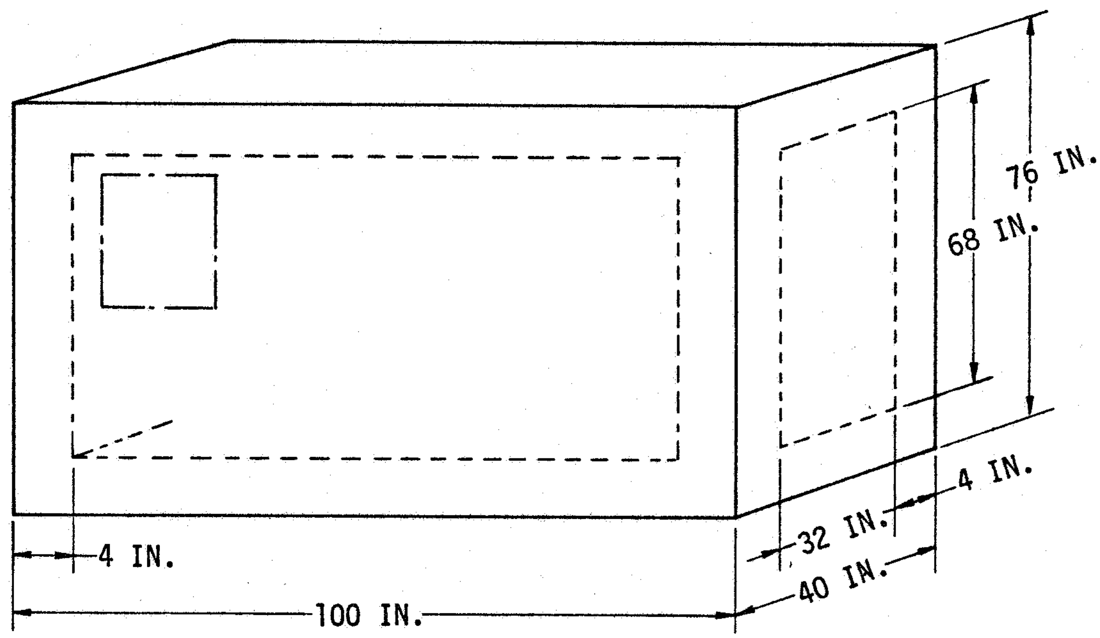


Figure A-8. Food Locker Dimensions

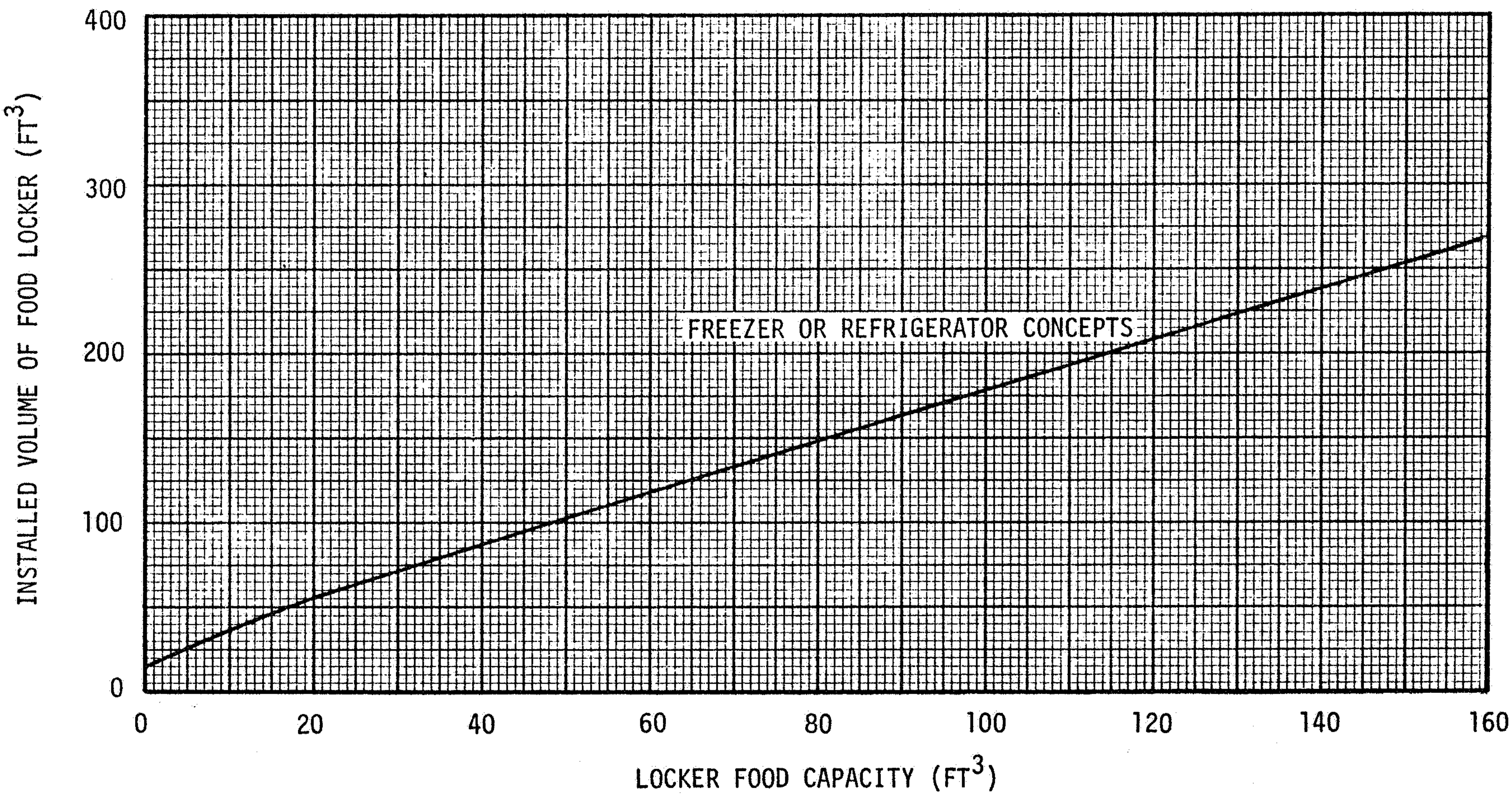


Figure A-9. Space Radiator Locker Volume for Various Capacities

A.1.4 Fin and Coolant Tube Analysis.

A.1.4.1 Fin and Coolant Tube Definition (Figure A-10).

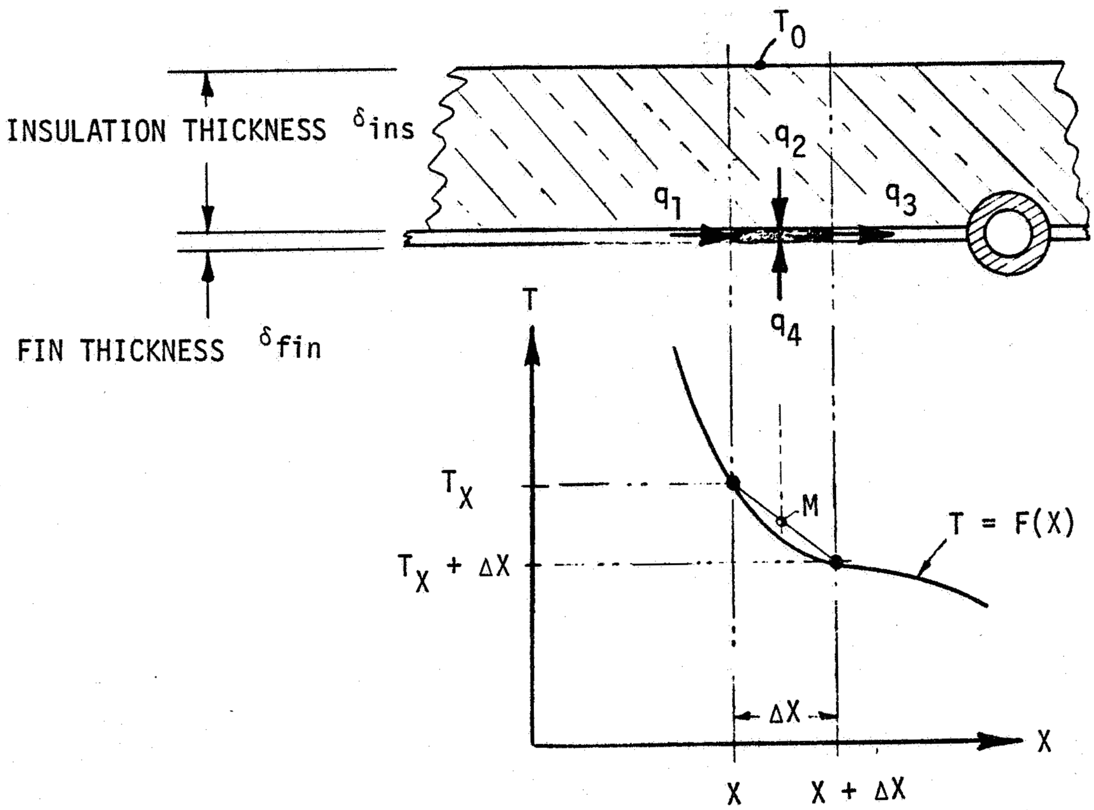


Figure A-10. Fin and Coolant Tube Parameters

Definition:

$$\left(\frac{dT}{dx}\right)_M = \frac{1}{\Delta X}\left(T_x - T_{x + \Delta x}\right)^{(-1)}$$

$$(-1)\left(\frac{dT}{dx}\right)_M \Delta X = T_x - T_{x + \Delta x}$$

$$(-1)\frac{d}{dx}\left(\frac{dT}{dx}\right)_M \Delta X = \left(\frac{dT}{dx}\right)_x - \left(\frac{dT}{dx}\right)_{x + \Delta x}$$

or

$$\left(\frac{dT}{dx}\right)_{x + \Delta X} = \left(\frac{dT}{dx}\right)_x + \left(\frac{d^2T}{dx^2}\right)_M \Delta X$$

A.1.4.2 Fin Element Analysis.

Heat Balance on Fin Element:

$q_1 + q_2 + q_4 = q_3$

now

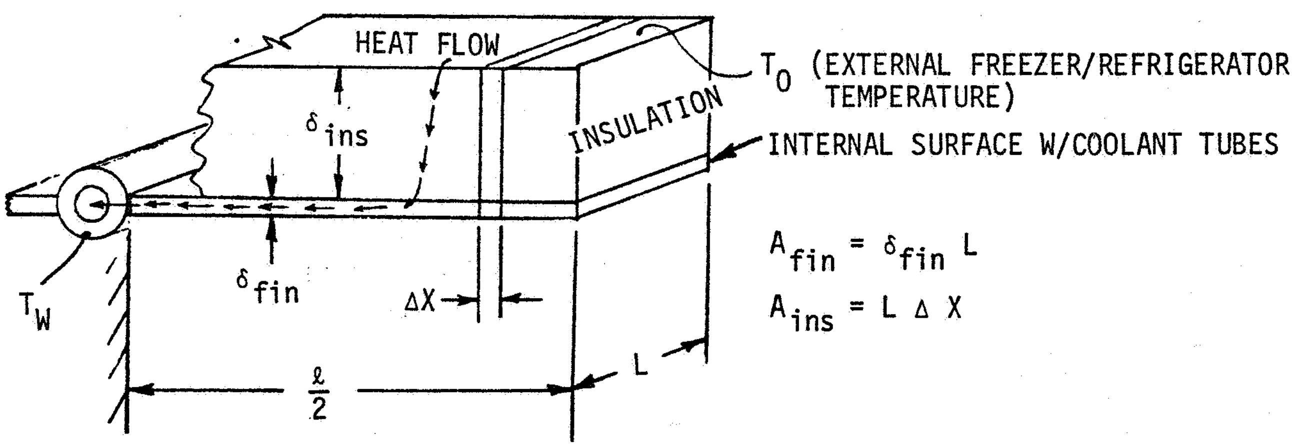
$$-KA_{fin}\left(\frac{dT}{dx}\right)_x + \left(\frac{KA}{\delta}\right)_{ins}(T_o - T_M) + 0 = -KA_{fin}\left(\frac{dT}{dx}\right)_{X + \Delta X}$$

$$-KA_{fin}\left(\frac{dT}{dx}\right)_x + \left(\frac{KA}{\delta}\right)_{ins}(T_o - T_M) = -KA_{fin}\left(\frac{dT}{dx}\right)_x - KA_{fin}\left(\frac{d^2T}{dx^2}\right)_M \Delta X$$

$$\frac{d^2T}{dx^2} = \beta^2 (T - T_o) \qquad (1)$$

where

$$\beta^2 \equiv \left(\frac{KA}{\delta}\right)_{ins} \times \left(\frac{1}{KA}\right)_{fin} (1/\Delta X)$$



$$\therefore \quad \beta^2 = \left(\frac{KA}{\delta}\right)_{ins} \times \frac{1}{\Delta X\ (KA)_{fin}} = \frac{K_{ins}}{K_{fin}\ \delta_{fin}\ \delta_{ins}}$$

Thus the general solution to the ordinary second order linear differential equation (1)

$$T - T_o = C_1 e^{\beta X} + C_2 e^{-\beta X} \qquad (2)$$

where C_1 and C_2 are constants of integration to be determined from boundary conditions below.

Boundary condition: at $x = 0$, $T = T_W$

thus equation (2) $$T_W - T_o = C_1 + C_2 \qquad (3)$$

Boundary condition: at $x = \frac{\ell}{2}$, $\frac{dT}{dx} = 0$

thus differentiating equation (2) $\frac{dT}{dX} = \beta C_1 \, e^{\beta X} - C_2 \, \beta e^{-\beta X}$

now

$$0 = C_1 \, E^{\beta \ell/2} - C_2 \, e^{-\beta \ell/2} \qquad (4)$$

$$C_2 = C_1 \, e^{\beta \ell}$$

from equations (3) and (4) $C_1 = \left(\frac{T_W - T_o}{1 + e^{\beta \ell}}\right) \quad C_2 = \left(\frac{T_W - T_o}{1 + e^{-\beta \ell}}\right)$

thus, the complete solution to equation (1) is

$$T - T_o = (T_W - T_o) \left[\frac{e^{\beta X}}{1 + e^{\beta \ell}} + \frac{e^{-\beta \ell}}{1 + e^{-\beta \ell}}\right] \qquad \text{OR}$$

in simplified form

$$\frac{T - T_o}{T_W - T_o} = \frac{\cosh \beta \, (\frac{\ell}{2} - X)}{\cosh \, (\beta \, \frac{\ell}{2})} \qquad (5)$$

now, the heat flow from the fin root into the coolant tube wall

$$q_{fin/wall} = -KA \left.\frac{dT}{dx}\right|_{x = 0} \qquad (6)$$

where

$$\frac{dT}{dx} = (T_W - T_o) \, \beta \left[\frac{e^{\beta X}}{1 + e^{\beta \ell}} - \frac{e^{-\beta \ell}}{1 + e^{-\beta \ell}}\right]$$

$$\left.\frac{dT}{dx}\right|_{x = 0} = (T_W - T_o) \, \beta \, \tanh \, (\beta \, \frac{\ell}{2}) \qquad (7)$$

now equation (6)

$$q_{fin/wall} = -KA \left.\frac{dT}{dx}\right]_{x=0} = \left(K_{fin}\ \delta_{fin}\ L\beta\right) \tanh\left(\beta \frac{\ell}{2}\right) (T_o - T_W) \tag{6A}$$

or, rearranging

$$q_{fin/wall} = \left(\frac{K}{\delta}\right)_{ins} L \frac{\ell}{2} \eta_f (T_o - T_W) \tag{6B}$$

where

$$\eta_f = \tanh \frac{\left(\beta \frac{\ell}{2}\right)}{\beta \frac{\ell}{2}}$$

(Double this value for a fully developed fin, i.e., half a fin is attached to either side of the coolant tube.)

(This expression is unity when temperature profile on fin is constant.)

A.1.4.3 Coolant Tube Analysis (Figure A-11).

Assume:

- $\bar{D} = D_o - \frac{\delta_{fin}}{2}$
- $\bar{T}_c = \frac{1}{2}(T_{c_i} + T_{c_o})$
- T_W is constant

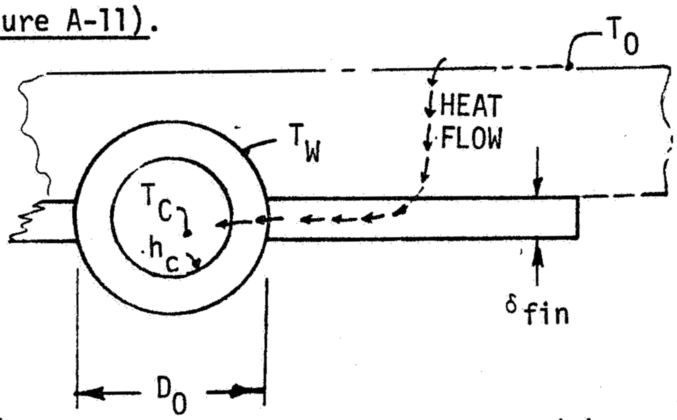


Figure A-11. Coolant Tube

thus

$$q_{wall/coolant} = h_c\ \pi\bar{D}\ L(T_W - \bar{T}_c) \tag{8}$$

also

$$q_{c_{wall/coolant}} = \omega_c\ Cp_c\ (T_{c_o} - T_{c_i}) \overset{or}{=} 2\ \omega_c\ Cp_c\ (\bar{T}_c - T_{c_i}) \tag{9}$$

and from equation (6B)

$$h_c\ \pi\ \bar{D}\ L(T_W - \bar{T}_c) = \left[\left(\frac{K}{\delta}\right)_{ins} L \frac{\ell}{2} \eta_f (T_o - T_W)\right] \times 2 \tag{10}$$

(Two-half fins required per unit tube length.)

A.1.5 Space Radiator Analysis.

A.1.5.1 Radiator Cross Section (Figure A-12).

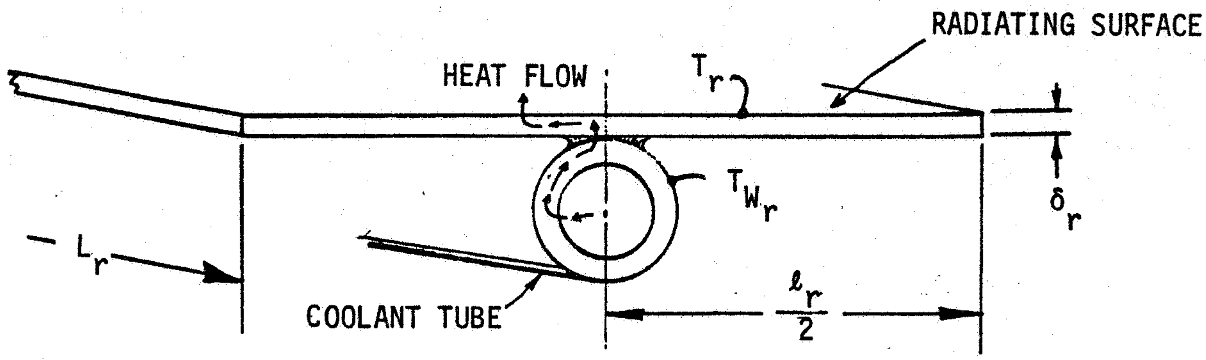


Figure A-12. Cross Section Diagram

A.1.5.2 Fin Analysis.

as per analysis of internal fin

$$K_r \delta_r \frac{d^2T_r}{dx^2} + \bar{h}_r (T_\infty - T_r) = 0 \qquad T_\infty \equiv \begin{array}{l}\text{Space}\\ \text{Temp}\end{array}$$

so

$$\text{at } X = 0, \quad T_r = T_{W_r} \text{ (assumed constant)}$$

$$\text{at } X = \frac{\ell_r}{2}, \quad \frac{dT_r}{dx} = 0$$

$$T = T_\infty = (T_{W_o} - T_\infty) \frac{\cosh \gamma \left(\frac{\ell_r}{2} - X\right)}{\cosh \gamma \left(\frac{\ell_r}{2}\right)}$$

where

$$\gamma^2 = \frac{\bar{h}_r}{K_r \delta_r}$$

at X = 0, the heat transferred to the fin from the wall of tube

$$q_{\text{wall/rad}} = h_r L_r \frac{\ell_r}{2} \eta_r (T_{W_r} - T_\infty) \qquad \text{where } \eta_r = \frac{\tanh \gamma \frac{\ell_r}{2}}{\gamma \frac{\ell_r}{2}} \tag{11}$$

likewise

$$h_{c_r} \pi \bar{D}_r L_r \left(\bar{T}_c - T_{W_r}\right) = \left[h_r L_r \frac{\ell_r}{2} \eta_f \left(T_{W_r} - T_\infty\right)\right] \times 2 \tag{12}$$

and

$$2 \omega Cp_c \left(\bar{T}_c - T_{c_i}\right) = h_{c_r} \pi \bar{D}_r L_r \left(\bar{T}_c - T_{W_r}\right) \tag{13}$$

A.1.5.3 Coolant Fin Summary.

- $2 \omega_c Cp_c \left(\bar{T}_c - T_{c_i}\right) = h_c \pi \bar{D} L \left(T_W - \bar{T}_c\right)$
- $h_c \pi \bar{D} \left(\bar{T}_c - T_W\right) + \left(\frac{K}{\delta}\right)_{ins} \ell \eta_f \left(T_o - T_W\right) = 0$
- $h_{c_r} \pi \bar{D}_r \left(\bar{T}_c - T_{W_r}\right) + h_r \ell_r \eta_r \left(T_\infty - T_{W_r}\right) = 0$
- $2 \omega_c Cp_c \left(\bar{T}_c - T_{c_i}\right) = h_{c_r} \pi \bar{D}_r L_r \left(\bar{T}_c - T_{W_r}\right)$

A.1.5.4 Coolant Film Coefficient.

Solve for coolant internal film coefficient

$$\frac{hc\ Di}{K_c} = \frac{2}{\pi} \frac{\omega Cp_c}{K_c L} \frac{1 - 8 \psi(\eta_1)}{1 + 8 \psi(\eta_1)} \qquad \text{where} \quad \eta_1 = \frac{\pi}{4} \frac{K_c L}{\omega\ Cp_c}$$

for

$\frac{\omega Cp_c}{K_c L} \leq 3$ (which is the expected range), the function $\psi(\eta_1) \approx 0$

so

$$\frac{hc\ Di}{K_c} = \frac{2}{\pi} \frac{\omega Cp_c}{K_c L}$$

internal film coefficient
for coolant

$$h_c = \frac{2}{\pi D_i L} \omega Cp_c \tag{14}$$

Solve for Fin effectiveness

$$\eta_f = \frac{\tanh\left(\beta \frac{\ell}{2}\right)}{\beta \frac{\ell}{2}} \qquad \text{where} \quad \beta \frac{\ell}{2} = \frac{K_{ins}}{K_{fin}\, \delta_{fin} \delta_{ins}} \left(\frac{\ell}{2}\right)$$

$$\eta_f = \frac{.155}{.1563} = .993 \qquad = \frac{.025\ (.5)}{90\ (.032/12)\ .333} = 0.1563\ ft^{-1}$$

A value close to unity indicates that the distribution of temperature on the fin is nearly constant.

A.1.5.5 <u>Example Space Radiator Computations</u>.

Let

T_{C_i} = -29°F

T_∞ = -460°F

T_o = 75°F

T_W = -10°F

K_{ins} = 0.025 Btu/hr-ft-°F

K_{fin} = 90 Btu/hr-ft-°F

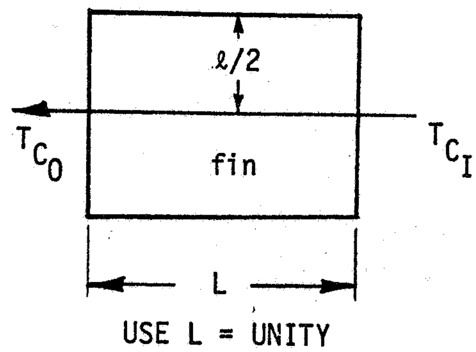
δ_{ins} = 4 in.(.333 feet)

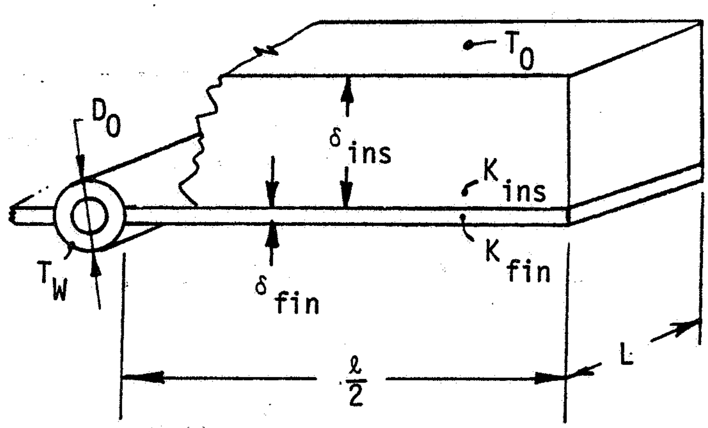
δ_{fin} = 0.032 in.

D_o = 0.250 in.

$\bar{D}$ = 0.234 in.

$\ell/2$ = 6.0 in.





Properties of 80% Ethylene Glycol at -10°F (-20°F) {-30°F}

K_c = 0.205 Btu/hr-ft-°F (.205)

Cp_c = 0.53 Btu/lb-°F (.52)

μ_c = 246 lb/hr ft (383.) {627.}

ρ_c = 70.2 lb/ft^3 (70.5) {70.6}

<u>Solve for freezer parameters</u>

from Paragraph A.1.5.3 and equation 14. . .

$$2\ \omega Cp_c \left(T_c - T_{c_i}\right) = 2\ \omega Cp_c \frac{\bar{D}}{D_i} (T_W - \bar{T}_c)$$

$$\bar{T}_c - T_{c_i} = \frac{\bar{D}}{D_i} (T_W - \bar{T}_c)$$

$$T_c \left(1 + \frac{\bar{D}}{D_i}\right) = T_{c_i} + \frac{\bar{D}}{D_i} T_W \qquad (15)$$

so

$$\left.\begin{aligned} \bar{T}_c &= \left[-29 + \frac{.234}{.218}(-10)\right] \frac{1}{1 + \frac{.234}{.218}} = -19.2°F \\ T_{c_o} &= 2\ \bar{T}_c - T_i = 2\ (-19.2) + 29 = -9.4°F \end{aligned}\right\} \text{coolant temperatures}$$

from Paragraph A.1.5.3 and equation 14. . .

$$\frac{2\ \omega Cp_c}{L} \frac{\bar{D}}{D_i} \left(\bar{T}_c - T_W\right) = \left(\frac{K}{\delta_{ins}}\right) \ell\ n_f \left(T_W - T_o\right)$$

so

$$W = \frac{1}{Cp_c} \left(\frac{K}{\delta_{ins}}\right) \ell\ n_f\ L \frac{D_i}{2\bar{D}} \left(\frac{T_W - T_o}{\bar{T}_c - T_W}\right) \qquad (16)$$

now

$$W = \frac{1}{.52}\left(\frac{.025}{.333}\right) 1\ (.993)\ \frac{.218}{2\ (.234)}\ \frac{(-10\ -75)}{(-19.2 + 10)} = 0.616\ \text{pph/ft}^2 \text{ of freezer interior fin area}$$

Recall equation (14)

$$h_c = \frac{2\ \omega C_p}{\pi D_i\ L} = 11.95\ \frac{\text{Btu}}{\text{hr-ft}^2\text{-°F}}$$

Solve for radiator parameters for freezers

Derive value for h_r, the overall radiation coefficient associated with surface of radiator. . .

simply

$$h_r\ A(T_t - T_\infty) = \varepsilon A \left[\sigma T_r^{\ 4} - \sigma T_\infty^{\ 4}\right]$$

$$h_r = \frac{\varepsilon\sigma T_r^{\ 4}}{T_r + 460} = 0.133\ \frac{\text{Btu}}{\text{hr-ft}^2\text{-°F}}$$

(assuming T_t = -18°F)

where. . .

ε = .90

T_∞ = -460°F

η_r = 1.0, so that radiator surface is isothermal.

now, let

$\ell_r \equiv \ell = 1.0$ ft.

$\bar{D}_r \equiv \bar{D} = 0.234$ in.

$D_{r_i} \equiv D_i = 0.218$ in.

$\eta_r \equiv 1.0 \rightarrow T_r = T_{W_r}$

$h_{c_r} \equiv h_c = 11.95$ Btu/hr-ft^2-°F

from Paragraph A.1.5.3 and equation 14. . .

$$\left(h_{c_r}\right) \pi\ \bar{D}_r \left(\bar{T}_c - T_{W_r}\right) + h_r\ \ell_r\ \eta_r \left(T_\infty - T_{W_r}\right) = 0$$

$$\left(\frac{2\ \omega C_p}{L}\frac{\bar{D}}{D_i}\right)\bar{T}_c - \left(\frac{2\ \omega C_p}{L}\frac{\bar{D}}{D_i}\right) T_{W_r} - h_r\ \ell_r\ \eta_r \left(T_{W_r}\right) = 0$$

so

$$T_{W_r} = \frac{\left(\frac{2\ \omega C_p}{L}\ \bar{D}/D_i\right)\ \bar{T}_c}{\frac{2\ \omega C_p}{L}\ \bar{D}/D_i + h_r\ \ell_r\ \eta_r} \tag{17}$$

now

$$T_{W_r} = \frac{2.065\ (-19.2)}{2.065 + .533} = -16.02°F$$ temperature of radiator surface for freezer concept.

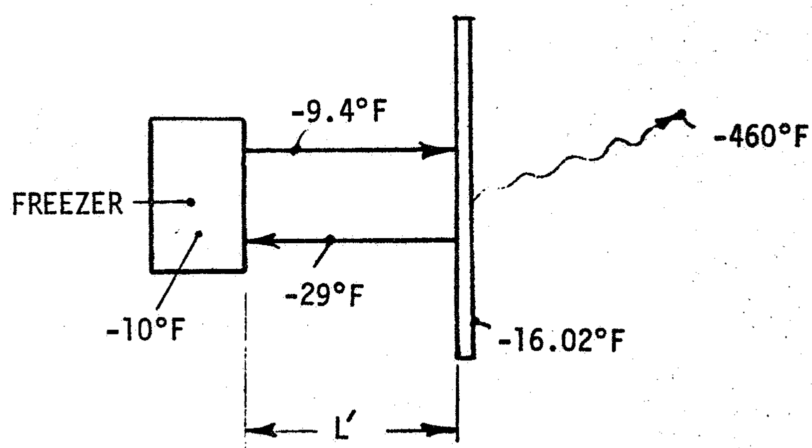
now, from equation (11)

$$Q_{\text{radiator heat flow}} = 58.8\ \frac{\text{Btu}}{\text{hr ft}^2}$$

and from equation (6B)

$$Q_{\text{freezer fin heat flow}} = 6.32\ \frac{\text{Btu}}{\text{hr ft}^2}$$

<u>Conclusion:</u> Use 0.1076 ft^2 radiator surface per 1.0 ft^2 freezer fin surface



USE AN OVERALL L′ = 100 FEET

A.1.6 <u>Power for Coolant Pump (Freezer)</u>.

Pressure drop through 100 foot lines.

$$\Delta P = \frac{128\ \mu\omega L'}{\rho\ g\ \pi D_i^4} = \frac{128 \times 627\ (.154)\ 100}{70.6 \times 32.2\ \pi\left(\frac{.218}{12}\right)^4}\left(\frac{1}{3600}\right)^2$$

$$\underline{\Delta P = 122.5\ \text{lb/ft}^2}$$

$$\text{Power} = \Delta P \times \frac{\omega}{\rho} = \frac{122.5}{70.6}\ (.616)\ (3.76 \times 10^{-4})\ \text{watts}$$

now

$\underline{\text{Watts} = 1.00 \times 10^{-4} \text{ watts/ft}^2 \text{ of freezer fin surface}}$

Neglect pumping power but assume that controls, valves, sensors and illumination uses 50 watts momentarily.

A.1.7 Weight Analysis for Space Radiator Hardware. This analysis is based on a "per ft^2 of interior freezer fin".

For the previously calculated values of. . .

Coolant coefficient, h_c = 2.81 Btu/hr-ft^2-°F

Coolant flow rate, ω = 0.154 lb/hr

Coolant tube ID, D_i = 0.218 in.

. . .the coolant velocity within the tube is

$$V = \frac{\omega}{\rho} \frac{4}{\pi D_i^2}$$

$$V = (.616) \left(\frac{1}{70.6}\right) \left(\frac{4}{\pi}\right) \left(\frac{1}{.218}\right)^2 \times \left(\frac{12 \text{ in}}{\text{ft}}\right)^2 \times \left(\frac{1 \text{ hr}}{60 \text{ min}}\right)$$

$$V = 0.564 \text{ ft/min}$$

This velocity shall be maintained regardless of the size of the space radiator freezer concept; therefore,

$$\omega = V \rho \frac{\pi}{4} D_i^2$$

$$\underline{\omega = 13.0 D_i^2} \qquad (18)$$

where ω is the coolant flow in lb/hr.

Because the coolant flow pump will operate on an 80 to 90-percent duty cycle, the effective flow rate must increase accordingly, while the coolant tube diameter varies as equation (18). From the thermal analysis of the locker wall, heat at 5.04 Btu/hr penetrates each square foot of freezer surface. However, use 125 percent of this value to account for other leaks and the duty cycle requirements.

Thus, on the per-square-foot basis, 0.616 lb/hr of coolant will remove 6.30 Btu/hr of locker heat losses. So, the total coolant flow required for any size freezer is. . .

$$\omega_{total} = \frac{(.616\ \text{lb/hr})}{(6.30\ \text{Btu/hr})}$$

See Figure A-4 for locker heat losses.

Recalling equation (18) and rearranging

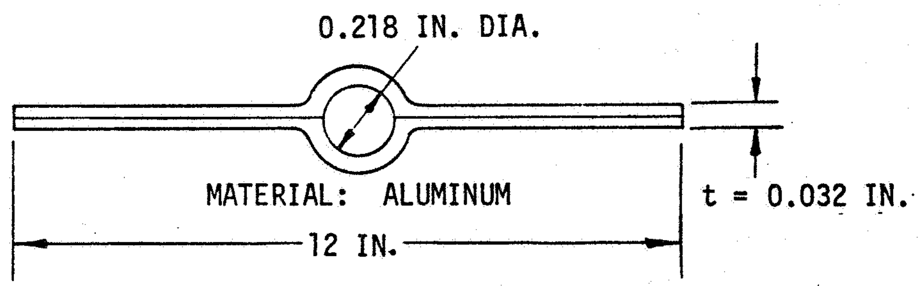
$$D_i = \sqrt{\frac{\omega_{total}}{13.0}}$$

$$D_i = \sqrt{\frac{1}{13.0} \times \frac{.616}{6.30}\ \{\text{locker heat losses}\}}$$

$$D_i = 0.0866\ \sqrt{\{\text{locker losses}\}}$$

Thus, for any size freezer locker, the locker losses will determine the internal diameter of the coolant transport tube that connects the locker circulation system to the external space radiator assembly.

Figures A-13 and A-14 present the weight and volume of space radiator hardware: 200 feet of coolant tube, 2 diverter valves, 1 coolant pump and motor. The weight and volume of the valves, pump, and motor were estimated from commercially available units. For the cross-section shown below, a radiator panel weight (per square foot) was found to be 0.47 pound total ÷ ft^2 of surface.



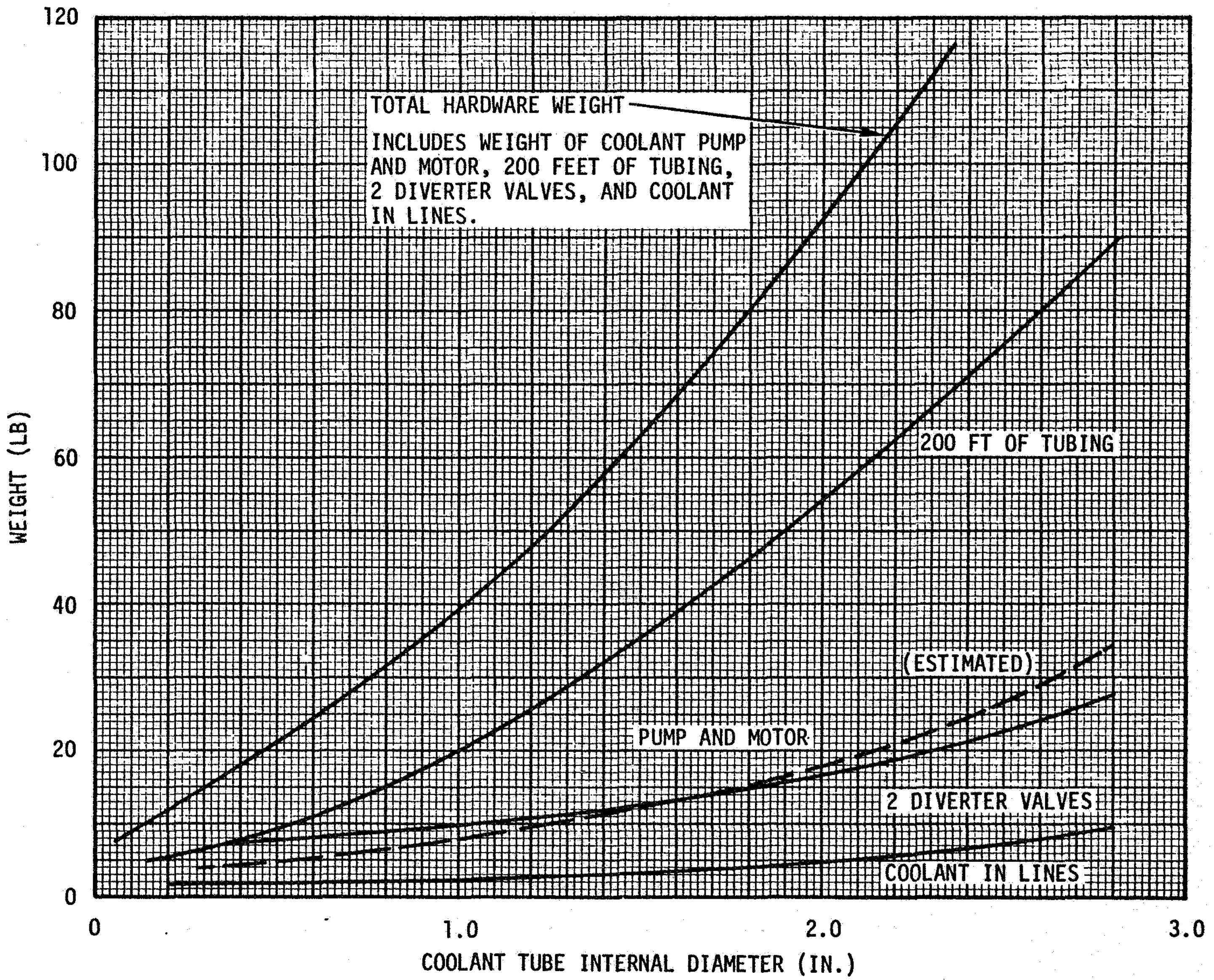


Figure A-13. Space Radiator System Weight for Various Coolant Tube Internal Diameters

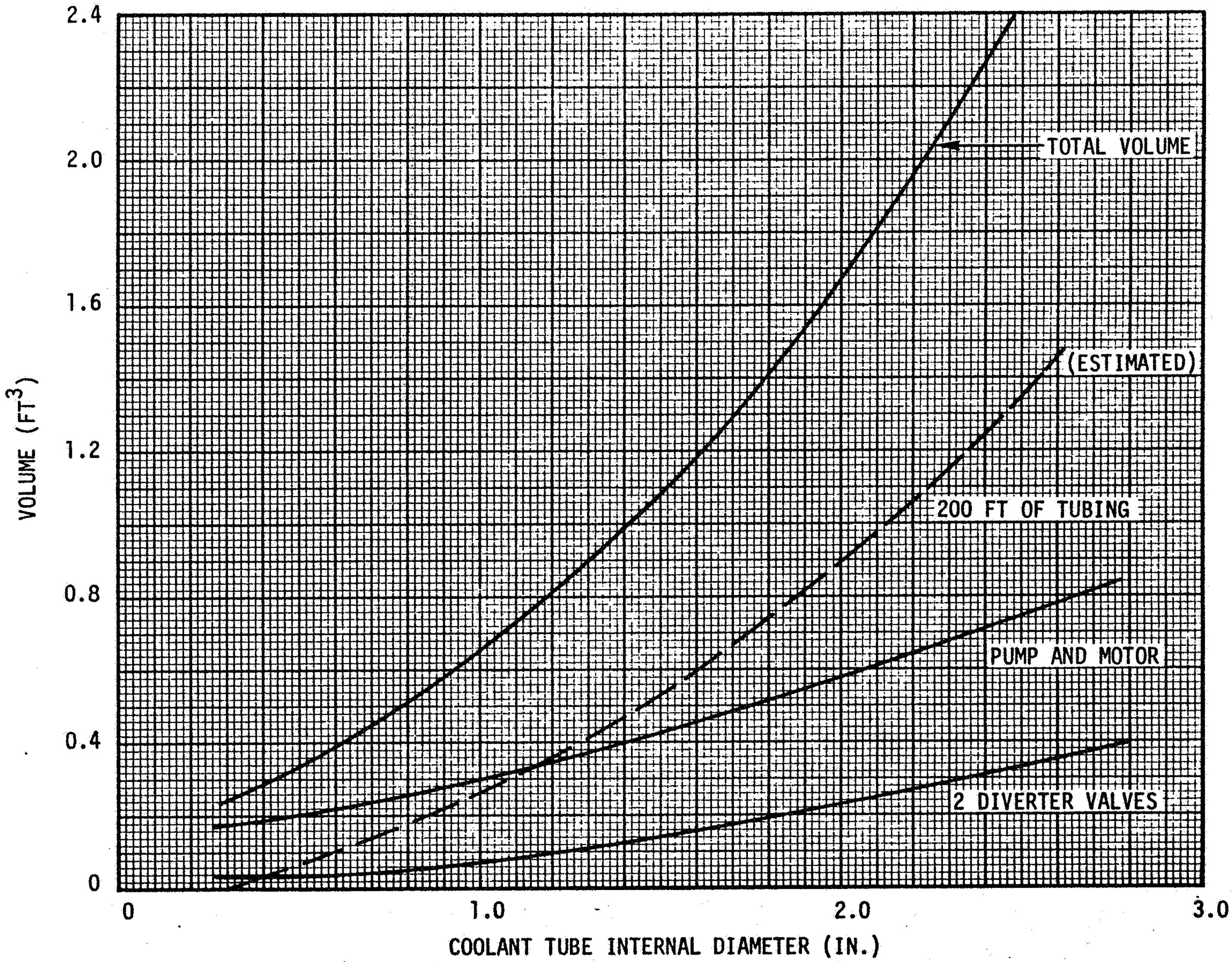


Figure A-14. Space Radiator System Volume for Various Coolant Tube Internal Diameters

Now, from the conclusion of radiator parameters for freezer concepts

$$A_{radiator} = (.1076)\ A_{freezer\ fin}$$

and from previous considerations, each square foot of freezer fin intercepts approximately 6.30 Btu/hr; that is,

$$A_{freezer\ fin} = \frac{1}{6.30}$$

See Figure A-4 for locker heat losses

wherein,

$$A_{radiator} = \frac{.1076}{6.30}\ \{\text{locker heat losses}\}$$

but

$$Wt_{radiator} = \left(.47\ \frac{\text{lbs}}{\text{ft}^2}\right)\left(\frac{.1076}{6.30}\right)\{\text{locker heat losses}\}$$

$$\underline{Wt_{radiator} = .0087\ \{\text{locker heat losses, Btu/hr}\}}$$

Two radiators would double this weight value.

A.1.8 Volume of Space Radiator. Assume the effective volume of the radiator assembly is a rectangular envelope around the unit. Thus, for each square foot. . .

$$Vol = (12\text{ in.})\ (12\text{ in.})\ (0.25\text{ in.})$$

$$Vol = 0.0208\ \text{ft}^3$$

$$V_{radiator} = \left(\frac{0.0208\ \text{ft}^3}{1\ \text{ft}^2}\right)\left(\frac{.1076}{6.30}\right)\{\text{locker heat losses}\}$$

$$\underline{V_{radiator} = 0.000356\ \{\text{locker heat losses, Btu/hr}\}}$$

Two radiators would double this volume value.

A.2 AIR CYCLE REFRIGERATOR/FREEZER ANALYSIS

The air cycle refrigerator technique uses air as the circulating refrigerant. To illustrate the operation of this system and its components, a thermodynamic analysis is presented for a typical air cycle refrigerator. For the analysis, a refrigerator capacity of 56 ft^3 of food was selected. Consequently, the heat leakage rate associated with the refrigerator locker was 248 Btu/hr or 73 watts leakage.

The 73 watts are continuously removed from the locker with an airflow circulating at 30 lbs/min. On Figures A-15 and A-16, air at ambient pressure P_0 is compressed to pressure P_2. A rotating compressor operating at a pressure ratio between 2.5 and 3.0 and air efficiency of 70 percent is typically employed in systems of this size. Figure A-15 indicates two separate compressors only to illustrate that the motor power enters the system through the compression process and that the compression process also loads the expansion turbine. In the process between states 2 and 3, heat is removed with almost no drop in pressure. The cooled air then enters the turbine where it expands to near-ambient pressure levels; the turbine supplies power to the compressor and delivers air to the refrigerator locker at a lower enthalpy (temperature) level, state point 4. The analysis was conducted using the air tables found in the appendix of <u>Mechanical Engineering Thermodynamics</u>, published by Prentice-Hall, Inc., 1953.

This analysis can be used to analyze freezer concepts noting that the assumed value for T_4 must be changed to -10°F internal freezer temperature.

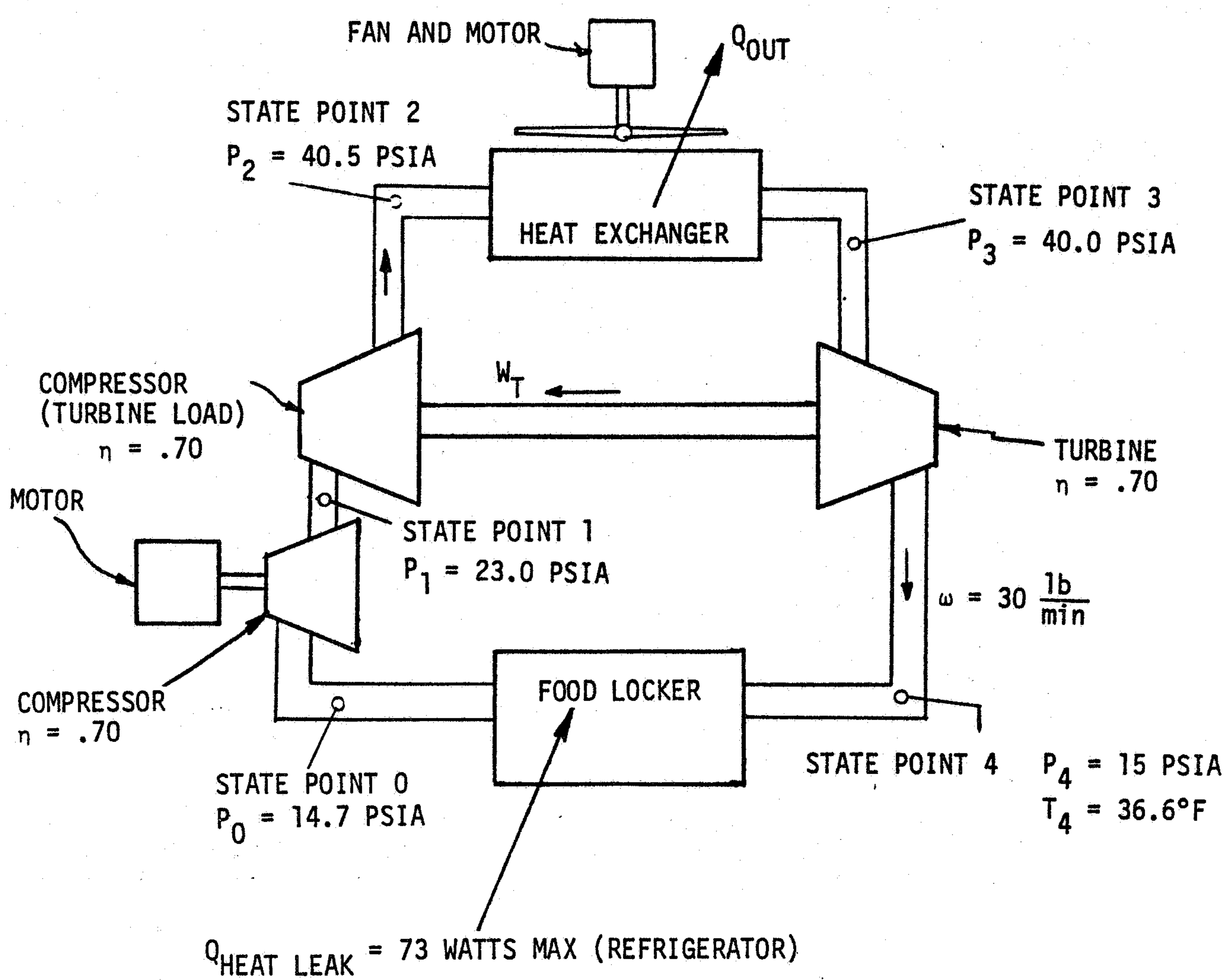
A.2.1 <u>Thermodynamic Analysis of Air Cycle Refrigerator (Figure A-15)</u>.

At state point 3:

A trial value of T_3 = 140°F will be assumed,
at T_3 = 140°F, in Air Tables we read. . .

h_3 = 143.5 Btu/lb

P_{r_3} = 2.00



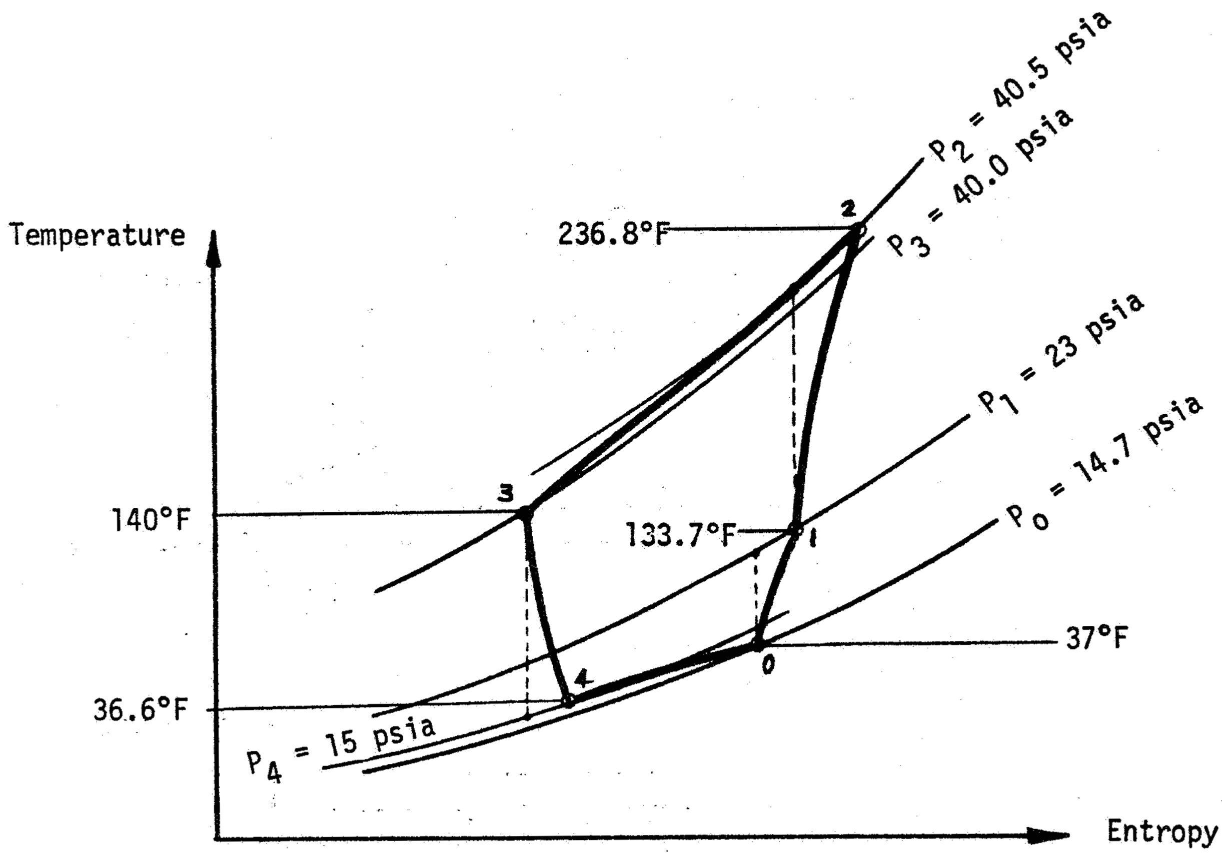
Assumed Values:

P_o	=	14.7 psia
P_4	=	15.0 psia
$(P_2 - P_3)$	=	0.5 psia
T_4	≈	40°F
ω	=	30 lb/min
$\eta_{compressor}$	=	.70
$\eta_{turbine}$	=	.70

$$2.5 < \left(\frac{P_2}{P_o}\right) < 3.0$$

$$2.5 < \left(\frac{P_3}{P_4}\right) < 3.0$$

Figure A-15. Air Cycle Schematic



State Point	Pressure (psia)	Temperature (°F)	Enthalpy (Btu/lb)
0	14.7	37.0	119.2
1	23.0	133.7	141.9
2	40.5	236.8	166.7
3	40.0	140.0	143.5
4	15.0	36.6	118.8

Figure A-16. Temperature-Entropy Plot of Air Cycle Refrigerator

now

$$P_{r_4} = P_{r_3} \left(\frac{P_4}{P_3}\right)$$

$$P_{r_4} = 2.00 \left(\frac{15}{40}\right)$$

$$P_{r_4} = .750$$

at $P_{r_4} = .750$, in Air Tables we read

$h_{4_s} = 108.16$ Btu/lb ("s" denotes isentropic state point)

$$T_{4_s} = -7.75°F$$

where $\left(T_3 - T_4\right) = .70 \left(T_3 - T_{4_s}\right)$

$$T_4 = T_3 - .70 \left(T_3 - T_{4_s}\right)$$

$$T_4 = 140 - .70\ (140 + 7.75)$$

$\underline{T_4 = 36.6°F}$ (temperature of air entering refrigerator)

If the resulting value for T_4 is unsuitable for refrigeration purposes, then the trial value of T_3 should be modified until the calculated value of T_4 is closer to 40°F.

and $\left(h_3 - h_4\right) = .70 \left(h_3 - h_{4_s}\right)$

$$h_4 = h_3 - .70 \left(h_3 - h_{4_s}\right)$$

$$h_4 = 143.5 - .70\ (143.5 - 108.16)$$

$h_4 = 118.80$ Btu/lb (enthalpy entering refrigerator)

energy balance on turbine

$$\omega h_3 = W_t + \omega h_4$$

$$W_t = \omega \left(h_3 - h_4\right)$$

now

$$W_t = (30 \text{ lb/min}) (60 \text{ min/hr}) (143.5 - 118.8)$$

$$\underline{W_t = 44{,}446 \text{ Btu/hr}}$$

energy balance on refrigerator locker

$$\omega\, C_p\, T_4 + Q_{heat\ leak} = \omega\, C_p\, T_o$$

$$(60 \text{ min/hr}) (30 \text{ lb/min}) (.240) (36.6) + (73 \text{ watts}) (3.413) = (60) (30) (.24)\, T_o$$

$$T_o = \frac{15800 + 248}{432}$$

$\underline{T_o = 37°F}$ (temperature of air leaving refrigerator)

at $T_o = 37°F$, in Air Tables we read

$$h_o = 118.78 \text{ Btu/lb}$$

$P_{r_o} = 1.038$ (properties of air leaving the refrigerator)

now, assume: $P_1 = 23$ psia:

$$P_{r_1} = P_{r_o}\left(\frac{P_1}{P_o}\right)$$

$$P_{r_1} = 1.038\left(\frac{23}{14.7}\right)$$

$$P_{r_1} = \underline{1.621}$$

at $P_{r_1} = 1.621$, in Air Tables we read

$$h_{1_s} = 135.0 \text{ Btu/lb}$$

$$T_{1_s} = 104.56°F$$

now, assuming the compressor has an efficiency of .70

$$\left(h_1 - h_o\right) = 1/.70 \left(h_{1_s} - h_o\right)$$

$$h_1 = h_o + 1.43 \left(h_{1_s} - h_o\right)$$

$$h_1 = 118.78 + 1.43\ (135.0 - 118.78)$$

$$\underline{h_1 = 141.98\ \text{Btu/lb}}$$

energy balance on compressor connected to turbine:

$$\omega h_1 + W_t = \omega h_2$$

and also $\left(h_2 - h_1\right) = 1/.70 \left(h_{2_s} - h_1\right)$

$$h_{2_s} = h_1 + W_t\ (.70/\omega)$$

$$h_{2_s} = 141.98 + 44{,}500\ (.70)\ \frac{1}{60 \times 30}$$

$$\underline{h_{2_s} = 159.23\ \text{Btu/lb}}\ \text{(based on assumption of } P_1 = 23\ \text{psia)}$$

now, to check the assumption of $P_1 = 23$ psia

$$P_{r_2} = P_{r_1}\left(\frac{P_2}{P_1}\right)$$

$$P_{r_2} = 1.621\left(\frac{40.5}{23}\right)$$

$$P_{r_2} = \underline{2.86}$$

at $P_{r_2} = 2.86$, in Air Tables we read

$$h_{2_s} = 158.78\ \frac{\text{Btu}}{\text{lb}}$$

The value of 158.78 is comparable to the aforementioned value of 159.28 Btu/lb; however, the trial value of P_1 was modified several times until the agreement of the enthalpy h_{2_s} values was sufficiently close. Therefore, P_1 is 23.0 psia and

$$\underline{T_1 = 133.7°F}$$

$$\underline{T_{2_s} = 205.75°F}$$

accordingly,

$$\left(h_2 - h_1\right) = 1/.70 \left(h_{2_s} - h_1\right)$$

$$h_2 = 141.98 + 1.43 \ (159.28 - 141.98)$$

$$\underline{h_2 = 166.73 \text{ Btu/lb}}$$

likewise,

$$\underline{T_2 = 236.8°F}$$

Determine the power required to drive the compressor between state points 0 and 1:

an energy balance on compressor shows

$$W_{in} = \omega \left(h_1 - h_o\right)$$

$$W_{in} = (30 \text{ lb/min}) \ (60 \text{ min/hr}) \ (141.98 - 118.78)$$

$$\underline{W_{in} = 41{,}750 \text{ Btu/hr}}$$

Using an overall motor/drive efficiency of 90 percent, the power of the motor is

$$W_{motor} = \frac{41{,}750}{3.413} \ \frac{1}{.90}$$

$$\underline{W_{motor} = 13{,}650 \text{ watts}} \ (18.3 \text{ Hp})$$

Energy balance on entire system

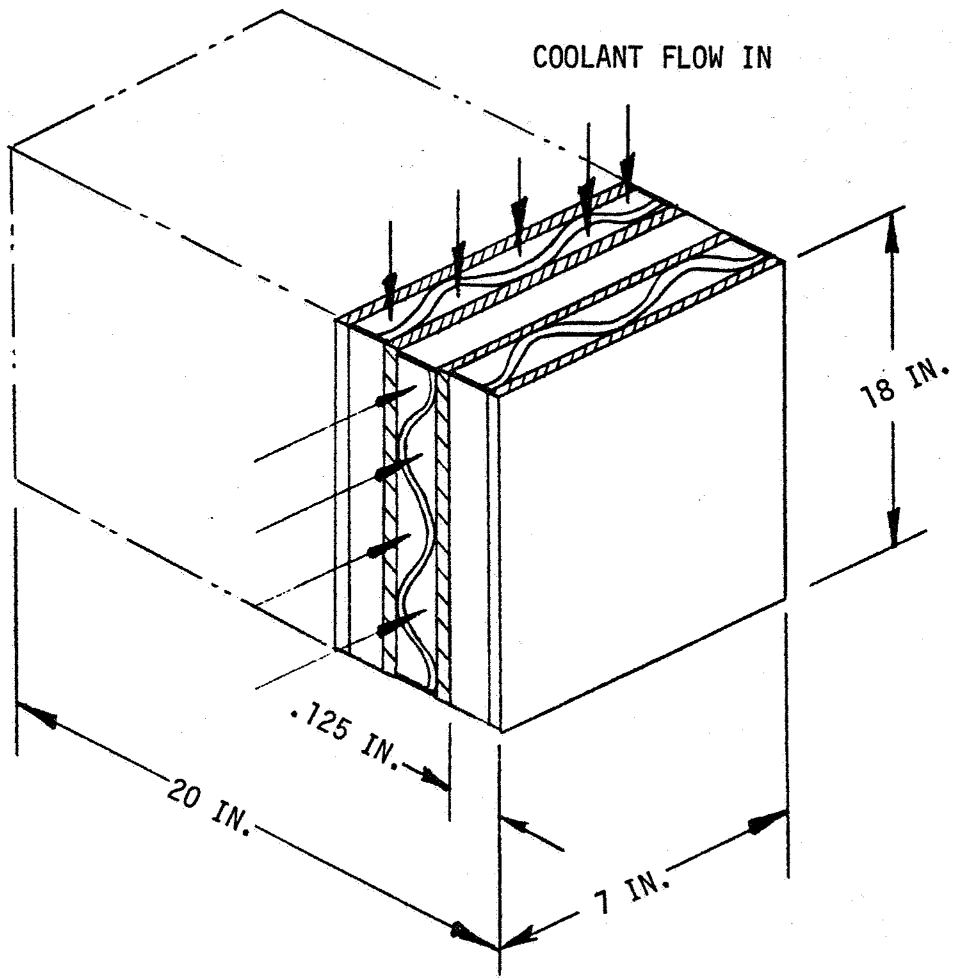
Energy in = Energy out

$$Q_{in} + W_{motor} = \omega \left(h_2 - h_3\right)$$

$$(73 \text{ watts})\ 3.413 + 41{,}750 \text{ Btu/hr} = (30 \text{ lb/min})\ (60 \text{ min/hr})\ (166.73 - 143.50)$$

$$\therefore\ 41{,}999 \cong 41{,}850$$

A.2.2 Heat Exchanger Analysis (Figure A-17).



A_c: Coolant free-flow area = 8 (7 in. x .100 in.) = 5.60 in^2

f: Friction factor, mean ≅ .040

ΔP_c: Pressure drop, coolant passages ≡ 2.0 psia

ε: Overall heat exchanger effectiveness ≅ .60

Figure A-17. Heat Exchanger Parameters

From the definition of effectiveness for a heat exchanger

$$T_{c_\sigma} = T_{c_i} + \beta\varepsilon\ \Delta T_{max} \quad \text{where}$$

T_{c_σ} = coolant temperature out

T_{c_i} = coolant temperature in $\cong$ 76°F

$\beta = (m\ C_p)_{air} / (m\ C_p)_{coolant} = \dfrac{30}{\omega_c}$

$\varepsilon = .60$

$\Delta T_{max} = T_{hot\ air\ in} - T_{coolant\ in} = (237 - 76) = 161°F$

ω_c = coolant flow rate, lb/min

so that,

$$T_{c_\sigma} = 76 + \left(\frac{30}{\omega_c}\right) (.60)\ (161)$$

$$\underline{T_{c_\sigma} = 76 + \frac{2900}{\omega_c}}$$

However, before T_{c_σ} can be evaluated, a value for ω_c must be determined:

$$\Delta P_c = \frac{fG^2}{2g_c\rho}\ \frac{4L}{D_h}$$

where

$\Delta P_c \equiv 2.0$ psia

$f = 0.04$

$g_c = 32.2\ ft/sec^2$

$\rho = 0.071\ lb/ft^3$

$L = 18$ in.

D_h = hydraulic diameter $= \dfrac{4A}{P_{wet}} = \dfrac{4\ (7 \times .10)\ 8}{2\ (7.10)} = 1.57$ in.

$$G \equiv \frac{\omega_c}{A_c} = \frac{\omega_c}{5.6}\left(\frac{1\ min}{60\ sec}\right)\left(\frac{12\ in}{ft}\right)^2 = .429\ \omega_c\ \frac{lb}{ft^2\text{-}sec}$$

ω_c = coolant flow rate, lb/min

now

$$G^2 = \left(\Delta P_c\right) 2\, g_c\, \rho\, D_h \times \frac{1}{4fL}$$

$$G^2 = (.02)\ 2\ (32.2)\ (.071)\ (1.57) \times \frac{144}{4\ (.04)\ (18)}$$

$$G^2 = 718.$$

$$\underline{G = 26.8\ \frac{lb}{ft^2\text{-sec}}}$$

but

$$G = .429\ \omega_c$$

$$.429\ \omega_c = 26.8$$

$\omega_c = 62.5\ \frac{lb}{min}$ fan driven coolant flow in heat exchanger

now, evaluate T_{c_σ}

$$T_{c_\sigma} = 76 + \frac{2900}{625}$$

T_{c_σ} = 122°F Temperature of coolant flow leaving heat exchanger

A.2.3 Summary of Air Cycle System.

- Power

a) Compressor motor		13,650
b) Fan motor		800
	Total power =	14,450 watts

- Weight

a) Turbine and compressor (estimated)		10.0
b) Heat exchanger (estimated)		18.0
c) Compressor motor (estimated)		150.0
d) Fan and motor (estimated)		40.0
e) Air ducts (estimated)		12.0
f) Food locker		375.5
	Total weight =	605.5

- Volume

a)	Turbine and compressor	0.60
b)	Heat exchanger w/fan, motor	3.08
c)	Compressor motor (estimated)	2.94
d)	Air ducts (estimated)	2.80
e)	Food locker	106.00
	Total volume =	115.42 ft^3

- Figure A-18 shows estimated levels for power, weight, and volume for the air cycle refrigerator.

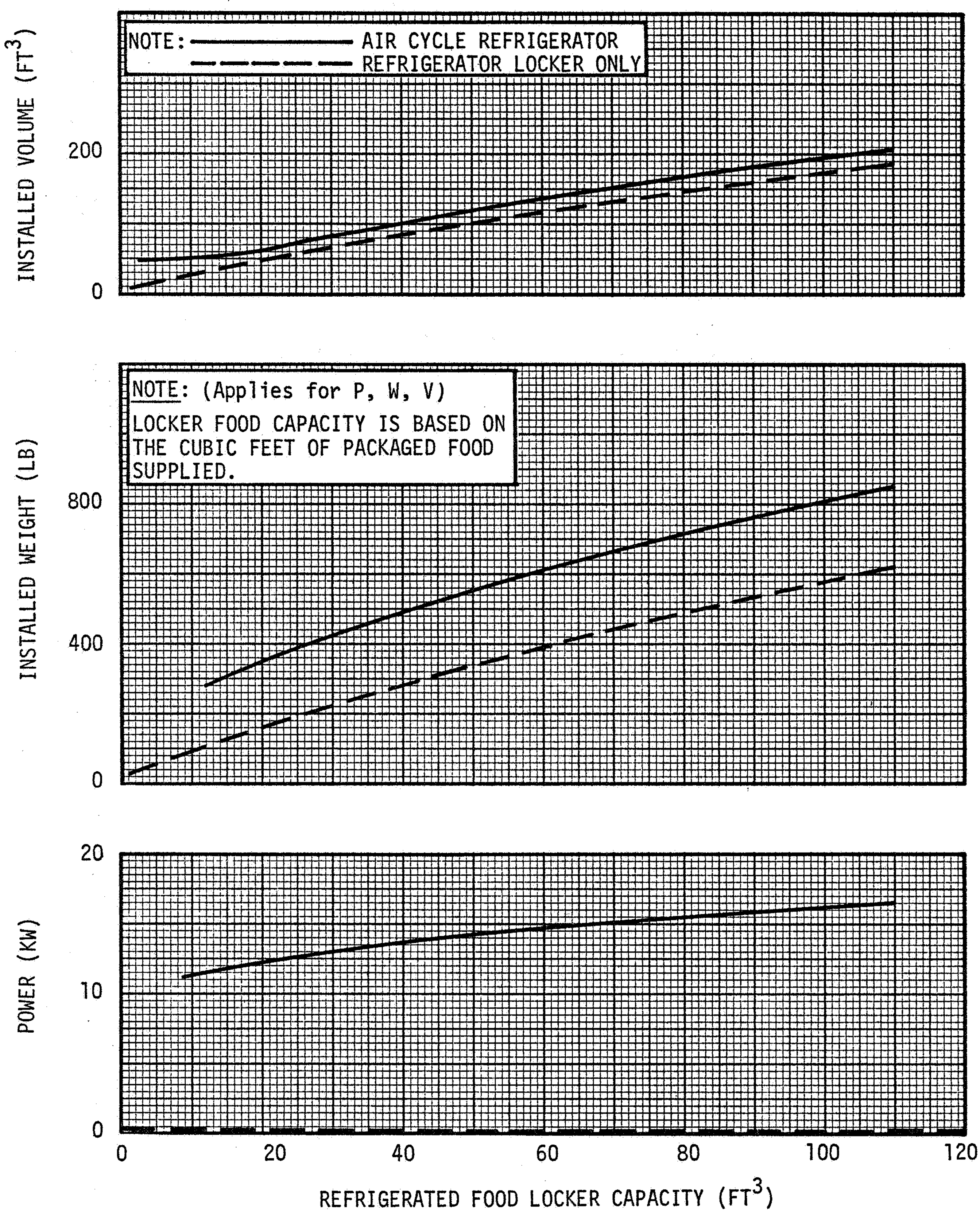


Figure A-18. Air Cycle Power, Weight and Volume for Various Refrigerator Food Capacities

A.3 HOT AIR CONVECTION OVEN ANALYSIS

The hot air convection heating oven raises the temperature of food to about 160°F from the frozen state of -10°F in 30 minutes. A fan located in the rear of the food compartment increases the circulation of the heated air over the food mass. A typical analysis of the hot air convection oven is presented below. The analysis starts by restricting the maximum tactile temperature of the oven (door) to 140°F.

Assume:
1. Surface temperature $T_0 \leqq 140°F$
2. $h_i \approx 6.70$ Btu/hr ft^2 °F (based on quick calculations)
3. Door facing is 0.125 in. thick
4. Door insulation is 0.75 in. thick
5. Radiation heat transfer mechanism predominant at T_0

A.3.1 Oven Door Analysis (Figure A-19).

Condition:

T_{gas} so that $T_0 \leqq 140°F$

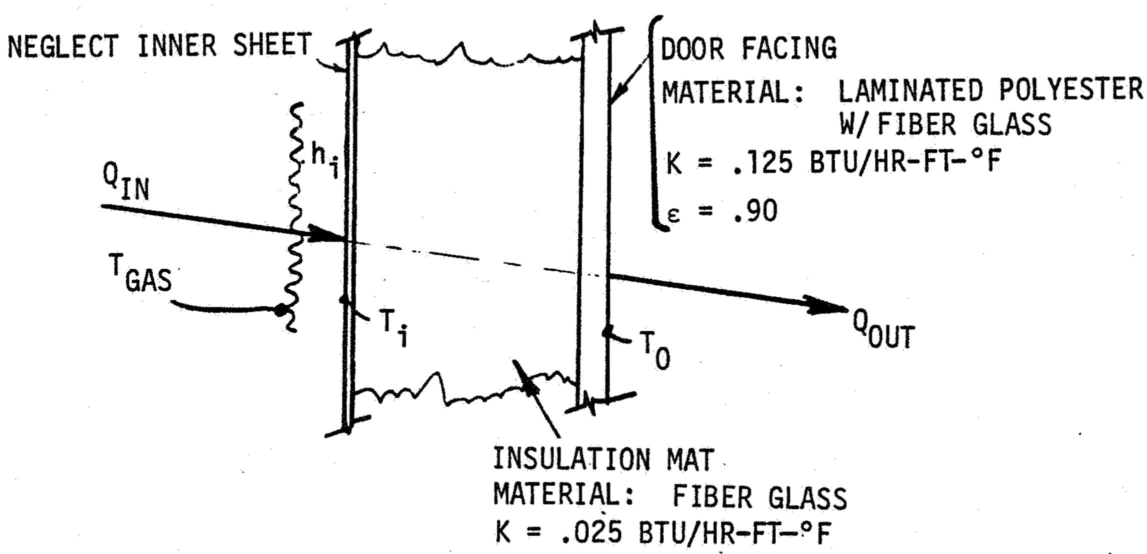


Figure A-19. Cross Section Through Oven Door

$Q_{in} = Q_{out}$

$$UA\left(T_g - T_o\right) = A\,\varepsilon_o\left[\sigma T_o^4 - \sigma T_\infty^4\right]$$

$$\frac{\left(T_g - 140\right)}{\frac{.125}{.125\ (12)} + \frac{.75}{.025\ (12)} + \frac{1}{6.7}} = .90\ (222 - 130)$$

Note: $Tg = T_{gas}$

$\underline{T_{gas} = 366°F}$

also

$$h_i\,A\left(T_g - T_i\right) = A\,\varepsilon_o\left(\sigma T_o^4 - \sigma T_\infty^4\right)$$

so

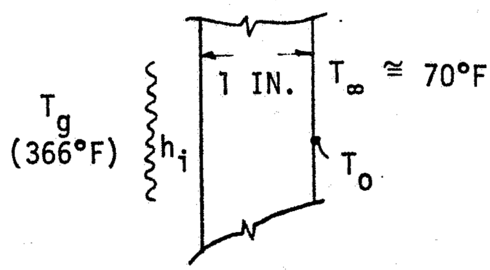
$\underline{T_i = 354°F}$

A.3.2 Steady State Losses (Worst Case).

Losses Through Top Surface

$$UA\,\Delta T = \frac{\left(T_g - T_o\right)A}{\frac{1}{.025\ (12)} + \frac{1}{6.7}} = .90\,A\left[\sigma T_o^4 - 135\right]$$

$$\therefore\ \frac{366 - T_o}{3.49\ (.90)} = \sigma T_o^4 - 135$$



$\underline{T_o = 131°F}$

$$\text{Loss} = \varepsilon A\left[\sigma T_o^4 - \sigma T_\infty^4\right]$$

$= .90\ (17 \times 16)\ 1/144\ [74]$

$= 126$ Btu/hr

Losses Through Bottom Surface

Loss = 126 Btu/hr

Losses Through Rear Surface

$$\frac{\left(T_g - T_o\right) A}{\frac{1}{.025\ (12)} + \frac{1}{9.25}} = .90\ A\ \left[\sigma T_o^{\ 4} - 135\right]$$

$$\frac{366 - T_o}{(3.45)\ .90} = \sigma T_o^{\ 4} - 135$$

$$T_o = 132°F$$

$$\text{Loss} = \varepsilon A\ \left[\sigma T_o^{\ 4} - \sigma T_\infty^{\ 4}\right]$$

$$= .90\ (14 \times 10)\ [75.5]\ \frac{1}{144}$$

$$= \underline{67\ \text{Btu/hr}}$$

Losses Through Sides

$$Q = \varepsilon A\ \left[\sigma T_o^{\ 4} - \sigma T_\infty^{\ 4}\right]$$

$$= .90\ [15.5 \times 10]\ 2\ [75.5]\ \frac{1}{144} = \underline{146.5\ \text{Btu/hr}}$$

Losses Through Door

$$Q = \varepsilon A\ \left[\sigma T_{140}^{\ 4} - \sigma T_\infty^{\ 4}\right]$$

$$= .90\ (14 \times 10)\ (87)\ \frac{1}{144} = \underline{76\ \text{Btu/hr}}$$

Summary of Heat Losses

Surface	Area (in^2)	Maximum Temperature (°F)	Heat Loss (Btu/hr)
Top	272	131	126
Bottom	272	131	126
Sides	155	132	146.5
Rear	140	132	67
Door	140	140	76
Total			541.5

A.3.3 Transient Power Required. This power is defined as the energy needed to raise the oven constituents to steady values.

a) Oven structural casing and door from 65°F to ~ 132°F
b) Insulation from 65°F to 243°F; {1/2 $(\bar{T}_i + \bar{T}_o)$ = 1/2 (354 + 132) = 243°F}
c) Plenum liners from 65°F to 354°F
d) Food compartment liners from 65°F to 354°F
e) Food mass from -10°F to 160°F
f) Food containers from -10°F to 265°F; {1/2 $(T_{food} + T_{gas})$ = 265°F}.

The heating capacity is sized for the above losses plus steady state leakage from surfaces. Neglect the thermal capacity of the air in the oven.

A.3.3.1 Calculations of Transient Power Required.

Structural Sheets

Oven Structural Casing

$$Wt = \rho \; t \; Area = (.10)\;(.030)\left[(12 \times 16.5) + (16.5 \times 15) + \frac{(10.5 \times 14.5)}{2}\right]2 = 3.3 \text{ lb}$$

$$Q = m\,C_p \frac{\Delta T}{\Delta\theta} = (3.13)\;(.23)\;(132 - 65)\;\frac{1}{.5} = \underline{96.5 \text{ Btu/hr}}$$

Oven Door (Polyester Facing)

$$Wt = \rho \; t \; A = (.070)\;(.125)\;[10.5 \times 14.5] - 1.332 \text{ lb}$$

$$Q = (1.332)\;.30\left(\frac{67}{.5}\right) = \underline{53.5 \text{ Btu/hr}}$$

Insulation Mat

$$Wt = \rho \; t \; Area = \left(\frac{2.40}{1728}\right)(1.0)\left[(12 \times 16.5) + (16 \times 16.5) + (16 \times 12)\;\frac{1.75}{2}\right]2$$

$$Q = (1.75)\;.12\;(354 - 65)\;\frac{1}{.5} = \underline{121 \text{ Btu/hr}}$$

Plenum Liners

$$Wt = \rho \; t \; Area = (.29)\;(.020)\left[(10 \times 14) + \frac{(12 \times 10)}{2} + (12 \times 14)\right]2 = 4.27 \text{ lb}$$

$$Q = (4.27)\;(.12)\;(354 - 65)\;\frac{1}{.5} = \underline{297 \text{ Btu/hr}}$$

Food Compartment Liners

$$Wt = \rho \cdot t \text{ Area} = (.29)\ (.020)\ \left[(10 \times 15.5) + \frac{(15.5 \times 14)}{2} + (1 \times 14)\ 2 + (14 \times 1.5)\right]\ 2 = 3.62 \text{ lb}$$

$$Q = (3.62)\ (.12)\ (289)\ \frac{1}{.5} = \underline{251 \text{ Btu/hr}}$$

Food Mass

$$Q_{\substack{\text{thaw from} \\ -10°F \text{ to } 32°F}} = \frac{m}{\Delta\theta}\left[30\%\ Cp_{food} + 70\%\ Cp_{ice}\right]\Delta T$$

$$= \frac{12\ (1.270)}{.50}\left[30\%\ (.40) + 70\%\ (.501)\right]\ (32 + 10)$$

$$= \underline{583 \text{ Btu/hr}}$$

$$Q \text{ required to change phase @ } 32°F = 12\ (1.270)\ [70\%]\ \frac{144}{.5} = \underline{2984 \text{ Btu/hr}}$$

$$Q_{\substack{\text{cook from} \\ 32°F \text{ to } 160°F}} = \frac{12\ (1.270)}{.50}\left[30\%\ (.40) + 70\%\ (1.00)\right]\ (160 - 32)$$

$$= \underline{3110 \text{ Btu/hr}}$$

Food Containers

Assume weight of the individual container as .25 pounds.

$\Sigma\ Wt = 12\ (.25) = 3.0$ lb

$$Q = \frac{(3.0)\ (.20)}{.50}\ (265 + 10) = \underline{330 \text{ Btu/hr}}$$

A.3.3.2 Summary of Power Required.

Oven Component	Weight (lb)	Power Required (Btu/hr)	Power Required (watts)
Structural sheets	4.46	150.0	
Insulation	1.75	121.0	
Plenum liners	4.27	297.0	
Compartment liners	3.62	251.0	
Food mass	14.80	6677.0	
Food containers	3.0	330.0	
Ambient leak	-	541.5	
TOTAL	31.9*	8367.0	2450 Watts

Use 2800-watt capacity heater

*Total oven weight

31.9 from above
5.0 fan/motor
2.0 heater/supports
1.0 controls/timers

39.9 pounds

A.3.4 Fan and Motor Size.

Surface Area in Plenum Regions

$$A_{\substack{\text{plenum}\\\text{overall}}} = 4(1 \times 15\text{-}1/2) + 2(1\text{-}1/2 \times 12) + 2(10 \times 16\text{-}1/2) + 2(10 \times 14) + 10(12 + 14) = 968 \text{ in}^2$$

since the flow splits equally, the effective surface of the plenum exposed is

$$A_{\text{plenum}} = 1/2\ (968)\ 1/144 = \underline{3.36 \text{ ft}^2}$$

Surface Area of Food Compartment

$$A_{\substack{\text{food}\\\text{compartment}\\\text{liners}}} = 2\left[(14 \times 12) + (10 \times 14) + (12 \times 10)\right] +$$

$$A_{\text{packages}} = 12\left[2(6.70 \times 4.75) + 2(6.70 \times 2) + 1(4.75 \times 2)\right]$$

$$A_{\substack{\text{food}\\\text{compartment}}} = (856 + 1200)\ 1/144 = \underline{14.28 \text{ ft}^2}$$

This area consists of the surface areas of the liners, the inner door, and food packages.

Turbulent Flow in Duct

$$h = .023\ \frac{K}{d} \left(\frac{d\omega}{\mu A}\right)^{.8} P^{1/3}$$

where

K (thermal conductivity)	=	0.019 Btu/hr-ft-°F
μ (viscosity)	=	1.61×10^{-5} lb/ft-sec
A (flow area)	=	(see below) ft^2
C_p (specific heat)	=	0.243 Btu/lb °F
P (Prandtl Number)	=	0.71
ω (flow rate)	=	(TBD) lb/sec
All evaluated at T_{film}	=	$1/2\ (T_g + T_i) = 300°F$

for the plenum, determine flow area (for above expression)

$$\text{Flow area of plenum only} = \frac{2(10 \times 1)\ 14 + 1\ (14 \times 1.5)\ 14}{2 \times 14 + 14} = 13.7 \text{ in}^2$$

$$= 0.095 \text{ ft}^2$$

$$D_{equiv.} = \frac{4A}{P_{wet}} = \frac{4\ (.095)}{2(1 + 10)\ \frac{1}{12}} = 0.207 \text{ ft.}$$

$$h_{in\ plenum} = .023\ \frac{.019}{.207} \left[\frac{.207\ \omega/2}{1.61 \times 10^{-5}\ (.095)}\right]^{.8} (.71)^{1/3}$$

$$\underline{= 13.75\ \omega^{.8}\ \frac{\text{Btu}}{\text{ft}^2\text{-hr-°F}}}$$

$$\text{Flow area of food compartment only} = (10 \times 12) - 6(4.75 \times 2.0)$$

$$= 63 \text{ in}^2$$

$$= 0.438 \text{ ft}^2$$

$$D_{equiv} = \frac{4A}{P_{wet}} = \frac{4(.438)\ 12}{(10 \times 12) + 12(4.75 + 2 + 2)} = \underline{0.0934 \text{ ft}}$$

$$h_{\substack{food\\compartment}} = .023\ \frac{.019}{.0934} \left[\frac{.0934\ \omega}{1.61 \times 10^{-5}\ (.438)}\right]^{.8} (.71)^{1/3}$$

$$= 8.27\ \omega^{.8}\ \frac{\text{Btu}}{\text{ft}^2\text{-hr-°F}}$$

A.3.5 <u>Heat Balance on Internal Surfaces (Size Fan)</u>.

$$Q_{heater} = Q_{into\ surfaces}$$

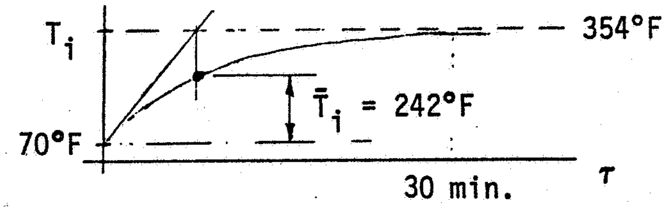
$$2800 \text{ watts} = 9560 \text{ Btu/hr} = hA_{plenum}\ (T_{gas} - \bar{T}_i) + hA_{\substack{food\\compartment}}\ (T_{gas} - \bar{T}_i)$$

$$9560 = \left[13.75\ \omega^{.8} \times 3.36 + 8.27\ \omega^{.8} \times 14.28\right] (366 - 242)$$

where

$$\omega^{.8} = 0.47$$

$$\underline{\omega = 0.394 \text{ lb/sec} = 308 \text{ scfm}}$$



Use $\bar{T}_i$ as an average surface (internal) temperature in initial calculations.

A.3.6 <u>Summary of Convection Oven Analysis</u>.

- Total weight = 31.9 + 5.0 (fan and motor) + 2.0 (heater and supports) + 1.0 (controls and timers) = <u>39.9 pounds</u>

- Installed volume = 16 x 13 x 19-1/4 (inches) = <u>2.55 ft^3</u>

- Total power = 2800 (heater) + 130 (motor) + 70 (controls and lights) = <u>3000 watts</u>

- Heat rejected = Q from (Oven* and Food Surfaces**)
  = 159 + 470 + 87 = <u>716 watts</u>

* Oven losses occur during cooking period plus 1.5 hours.
** Assume food cooling from 160°F to 100°F in 20 minutes = 470 watts
** Assume containers cooling from 265°F to 100°F in 20 minutes = 87 watts

A.4 MICROWAVE HEATING OVEN ANALYSIS

The analysis of the microwave heating oven is primarily concerned with determining the power required to raise the food temperature as well as determining the power losses that exist during the warming process. The following analysis will determine the requirements of an oven capable of heating food for 12 crewmembers. The oven is sized for 1.27 pounds of frozen food with a density of 50 lb/ft^3. For the analysis, four food packages measuring 2.0 in. x 7.7 in. x 8.55 in. will be used. The food will be heated from -10°F to 160°F.

A.4.1 Power Analysis. The power required to warm supplies for 12 men will be presented in three steps assuming 70% of the wet food mass is water.

-10°F to 32°F

$$Q_1 = \frac{m}{\Delta\theta}\left[70\%\ Cp_{ice} + 30\%\ Cp_{food}\right]\Delta T$$

$$Q_1 = \frac{12(1.27)}{0.5}\,[.70 \times .501 + .30 \times .40]\ 42$$

$$Q_1 = \underline{602\ \text{Btu/hr}}$$

32°F to 32°F Δphase

$$Q_2 = (70\%)\ m\ \frac{\Delta H}{\Delta\theta}$$

$$Q_2 = (.70)\ 12(1.27)\ \frac{144}{0.5}$$

$$Q_2 = \underline{3070\ \text{Btu/hr}}$$

32°F to 160°F

$$Q_3 = \frac{m}{\Delta\theta}\left[70\%\ Cp_{water} + 30\%\ Cp_{food}\right]\Delta T$$

$$Q_3 = \frac{12(1.27)}{0.5}\,[.70 \times 1.0 + .30 \times .40]\ 128$$

$$Q_3 = \underline{3190\ \text{Btu/hr}}$$

$Q_{food\ heating} = 602 + 3070 + 3190 = 6862$ Btu/hr

$Q_{food\ heating} = \underline{2000 \text{ watts}}$

$$\text{Power} = \frac{2000}{\eta}$$

$\underline{\text{Power} = 4000 \text{ watts}}$

A.4.2 Weight and Volume Calculations. The construction of the food cavity is a stainless steel shell. The outer case effectively insulates the control and power supply region and may be a lightweight phenolic. The space between the inner and outer shells are filled with fiber glass insulation only when the microwave oven is augmented with a radiant heating element; otherwise, very little thermal energy is evolved in the food cavity.

The expression for the installed volume is:

$$\text{Vol} = L \times W \times H$$
$$\text{Vol} = 30 \times 24 \times 16.5$$
$$\underline{\text{Vol} = 6.90 \text{ ft}^3} \text{ for a 12-man oven}$$

Because the dimensions of the above microwave oven concept are similar to a commercial unit of comparable power output, the installed weight can be estimated at 192 pounds.

A.4.3 Heat Rejected Into the Cabin Atmosphere. The heat that enters the cabin atmosphere during the preparation (and eating) cycle comes from the inefficiency in the microwave power supply and from the cooling of the meal prior to consumption. Because the overall efficiency of the microwave oven is 50 percent, a heat rate equal to that supplied to the food leaves the power supply and related equipment. Thus, the overall oven loss is

$$q_{oven\ loss} = \underline{2000 \text{ watts}}$$

Now, it is assumed that the food cools from 160°F to 100°F in approximately 20 minutes before completion of eating. The expression for this heat loss is

$$q_{food\ cool\text{-}off} = m\ Cp\ \frac{\Delta T}{\Delta \theta}$$

$m = 12 \text{ men} \times 1.27 \frac{\text{lb food}}{\text{man}}$

$C_p = 0.82$ Btu/lb °F

$\Delta T = 160 - 100°F$

$\Delta\theta = 20$ minutes

$q_{\text{food cool-off}} = 2250$ Btu/hr

$q_{\text{food cool-off}} = \underline{660 \text{ watts}}$

Total heat rejected to cabin atmosphere

$Q_{\text{rejected}} = 2000 + 660 = \underline{2660 \text{ watts}}$

A.5 RESISTANCE HEATING OVEN ANALYSIS

The analysis of the radiant warming oven is primarily concerned with determining the power required to raise the temperature of the frozen food from -10°F to the 160°F serving level as well as determining the power losses that exist during the warming process. The following analysis will determine the power, weight, and volume requirements of an oven capable of heating food for 12 crewmembers. The oven will be sized for 1.27 pounds of frozen food with a density of 50 lb/ft^3. For this analysis, four packages of frozen food measuring 2.0 in. x 7.7 in. x 8.55 in. will be used. The chamber is limited to 4 inches in height because food warming efficiency in the radiant oven falls off quickly for food thicknesses greater than 2 inches; that is, heating time and thermal losses increase.

A.5.1 Power Analysis. The power required to warm the frozen food for 12 men was calculated previously in the microwave oven computations. The power input to the food amounted to 6862 Btu/hr or approximately 2000 watts.

For the expression describing the electrical power input necessary to deliver this 2000 watts, an overall operating efficiency for the radiant oven concept must be determined. To ascertain this efficiency using analytical techniques would involve a digital computer program to solve a complex transient radiation analysis; that would involve multiple view factors, radiative couplings, and fixing the geometry associated with individual oven configurations. However, the efficiency of commercial radiant ovens is slightly superior to the microwave warming principle, but not equal to the hot air forced-convection concept.

This would place the efficiency between 50 percent and 62 percent; 60 percent was the chosen efficiency for the radiant oven. Thus,

$$\text{Power} = \frac{2000}{\eta} = \frac{2000}{.60}$$

$$\underline{\text{Power} = 3334 \text{ watts}}$$

A.5.2 Weight and Volume Calculations. The construction of the oven is stainless steel to minimize cleaning operations. An inch of thermal insulation surrounds the food warming chamber; two inches of insulation is used above the infrared element. Controls and indicators are sufficiently isolated from the heat of the heating chamber. Weight calculations indicate the following values:

Weight of fiber glass = 3.85 lb
Weight of stainless sheets = 28.1 lb
Weight of heating element, controls = 9.0 lb

The total installed weight of radiant oven = 40.95 lb

The expression for the installed volume is:

$$\text{Vol} = 27 \times 18.5 \times 7$$
$$\text{Vol} = 2.02 \text{ ft}^3$$

A.5.3 Heat Rejected into the Cabin Atmosphere. The energy that enters the cabin atmosphere during the preparation (and eating) cycle comes from stray radiation in the heating chamber. Approximately 40 percent of the electrical power supplied to the oven leaves in the form of losses. Thus, 40 percent of the energy supplied is:

$$q_{\text{oven loss}} = .40\ (3334)$$

$$q_{\text{oven loss}} = \underline{1334 \text{ watts}}$$

If the food cools from 160°F to approximately 100°F in 20 minutes before completion of eating, the expression for the heat rejected to cabin atmosphere is:

$$q_{\text{food cool-off}} = m\ Cp\ \frac{\Delta T}{\Delta \theta}$$

$$m = 12 \text{ men} \times 1.27\ \frac{\text{lb food}}{\text{man}}$$

$$Cp \approx 0.82 \text{ Btu/lb °F}$$

$$\Delta T = 160 - 100\text{°F}$$

$$\Delta \theta = 20 \text{ minutes}$$

$$q_{\text{food cool-off}} = \underline{660 \text{ watts}}$$

Total heat rejected during warming/eating cycle:

$$Q_{\text{rejected}} = 1334 + 660 = \underline{1994 \text{ watts}}$$

A.6 SELF HEATING FOOD PACKAGE ANALYSIS

The analysis of the self-heating food packages is primarily concerned with determining the power required to raise the food temperature to serving levels as well as determining the thermal losses that exist during the warming process. The self-heating package relies on the electrical resistivity of aluminum foil to introduce heat into the food. The foil is integrated directly into the food package, either laminated into a polyethylene bag or bonded to the surface of a paper board package.

For the purpose of this analysis, it is assumed that the internal portion of the food will be heated by conduction from the surface inward to 160°F in 30 minutes. The losses leaving the surface of the food package are primarily radiant. A typical distribution of transient temperatures for the self-heating packages is illustrated in Figure A-20.

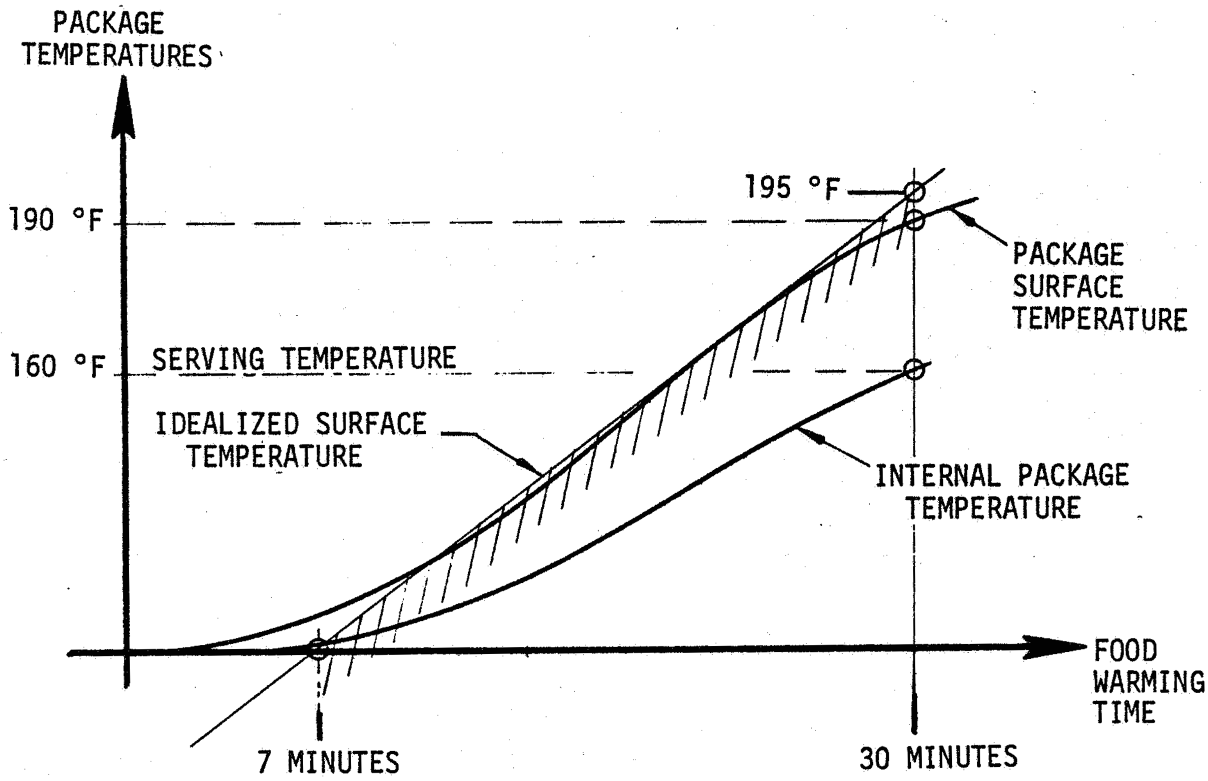


Figure A-20. Transient Temperature Distribution Associated with Warming the Self-Heating Food Package

A.6.1 Heat Loss and Power Analysis. Note that as the internal package temperature reaches the 160°F serving level, the surface of the package where the heating foil is located will typically be 30°F higher. To simplify the calculations, an idealized linear distribution will be used to approximate the transient temperature response at the surface. Thus, the radiation losses emanating from the surfaces will be based on an idealized temperature that commences to rise 7 minutes after the food warming current is initiated and increases to a peak of 195°F. The expression for the surface losses in Btu/hr is. . .

$$Q_{loss} = \left(A \times \varepsilon\right)_{surface} \left(\sigma T_s^4 - \sigma T_o^4\right)$$

where

A = square feet of package surface area

ε = .50, surface emissivity

T_s = 195°F, surface temperature

T_o = ambient wall temperature

The power required to warm the food from -10°F to 160°F is based on the daily food consumption rate of 1.27 pounds food per man. The power required to warm supplies for 6 men is presented in three steps below, assuming 70 percent of wet food mass is water.

<u>-10°F to 32°F</u>

$$Q_1 = \frac{m}{\Delta\theta}\left[70\%\ Cp_{ice} + 30\%\ Cp_{food}\right]\Delta T$$

$$Q_1 = \frac{6(1.27)}{0.5}\left[.70 \times .501 + .30 \times .40\right] 42$$

$$Q_1 = \underline{301\ \text{Btu/hr}}$$

<u>32° to 32°F Δphase</u>

$$Q_2 = m\ \Delta H\ (70\%)\ \frac{1}{\Delta\theta}$$

$$Q_2 = 6(.127)\ 144(.70)\ \frac{1}{0.5}$$

$$Q_2 = \underline{1535\ \text{Btu/hr}}$$

<u>32°F to 160°F</u>

$$Q_3 = \frac{m}{\Delta\theta}\left[70\%\ Cp_{water} + 30\%\ Cp_{food}\right]\Delta T$$

$$Q_3 = \frac{6(1.27)}{0.5}\left[.70 \times 1.0 + .30 \times .40\right] 128$$

$$Q_3 = \underline{1595\ \text{Btu/hr}}$$

$$Q_{food\ heating} = 301 + 1535 + 1595 = 3431\ \text{Btu/hr}$$

$$Q_{food\ heating} = \underline{1000\ \text{watts}}$$

Now, determine losses from surface of package. . .

Using a frozen food density of 50 lb/ft^3, the size of the food package for 6 crewmen is idealized as a package 8.55 inches x 7.70 inches x 4.0 inches; this yields a surface area of:

$$A = 2(L \times W) + 2(L \times H) + 2(H \times W)$$

$$A = [2(8.55 \times 4.0) + 2(8.55 \times 7.70) + 2(7.70 \times 4.0)]/144$$

$$A = \underline{1.814\ ft^2}$$

now,

$$Q_{loss} = \left(A \times \varepsilon\right)_{surface} \left(\sigma T_s{}^4 - \sigma T_o{}^4\right)$$

$$Q_{loss} = (1.814 \times .50)\ (315 - 157)$$

$$Q_{loss} = \underline{143.2\ Btu/hr}\ \text{(maximum value)}$$

But since the losses act only during the 23-minute interval from 7 minutes to 30 minutes after the electrical current is initiated, the lost energy amounts to:

$$Q_{loss} = (143.2\ Btu/hr) \times (23/60\ hour) \times .5$$

$$Q_{loss} = \underline{27.5\ Btu}$$

Thus, the total energy supplied during the 30-minute warming period is:

$$Energy = Q_{food\ heating} \times 1/2\ hour + Q_{loss}$$

$$Energy = (3431) \times 0.5 + (27.5)$$

$$Energy = \underline{1743.5\ Btu}$$

$$Energy = \underline{511.1\ watt\text{-}hours}$$

Peak power requirements occur at the end of the heating cycle when losses are maximum. The peak power required for the 6-man self-heating food package concept is:

$$\text{Power (max)} = Q_{\text{food heating}} + Q_{\text{loss (max)}}$$

$$\text{Power (max)} = 3431 \text{ Btu/hr} + 143.2 \text{ Btu/hr}$$

$$\text{Power (max)} = \underline{3574 \text{ Btu/hr}}$$

A.6.2 Weight and Volume. Weight and volume estimates for the self-heating package concept are based on a moderately small housing for the timing devices, switches and indicator lights, and clamp-like electrical terminals.

A.7 ELECTRICALLY HEATED FOOD TRAY ANALYSIS

The analysis of the electrically heated food trays is concerned with the food, the food cavities, and the heat required to raise the temperature of the cavity region. Assume that the size of the cavities accepts two food packages: 4 inches diameter by 1-3/8 inch deep, and 2.75 inches diameter by 1-3/8 inch deep. A cross section of one typical cavity region is shown in Figure A-21.

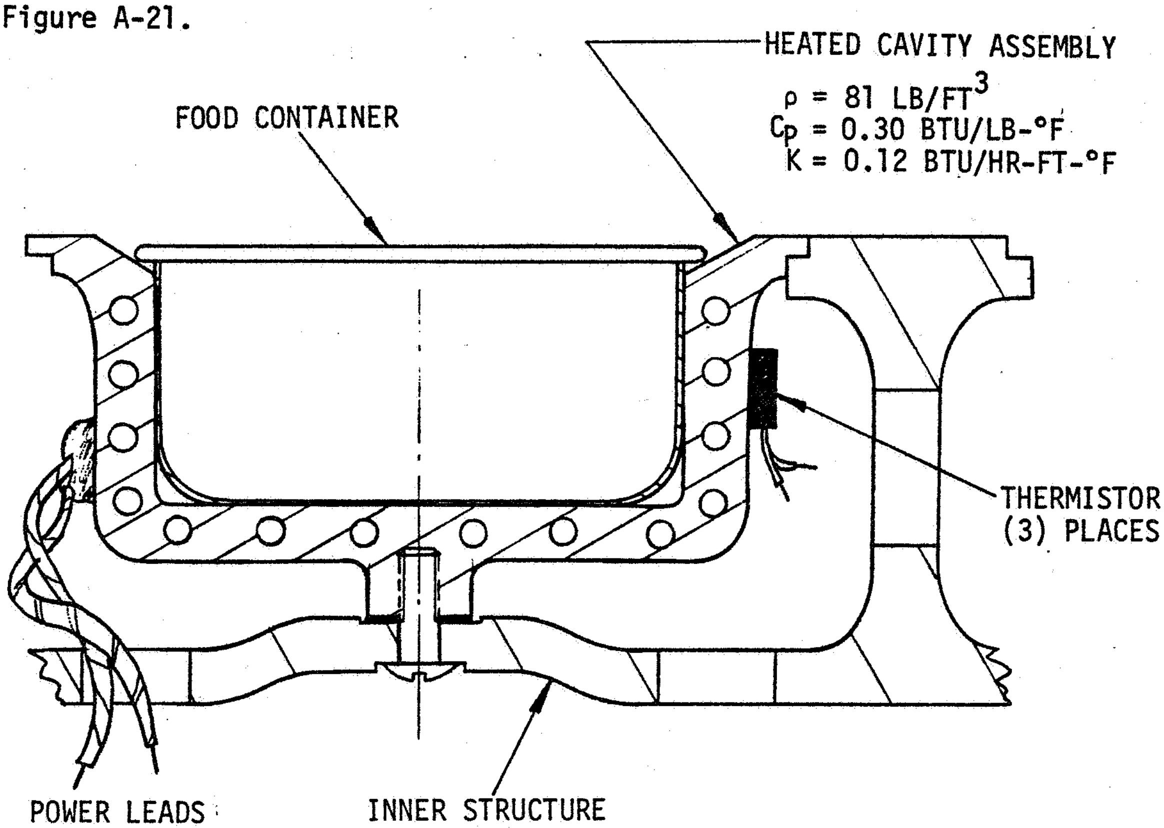


Figure A-21. Food Container Cross Section

A.7.1 Thermal Analysis of Cavity for Larger Food Container.

$$\text{Mass of cavity walls} = \left[\pi\ D\ h + \frac{\pi D^2}{4}\right] \rho \times t$$

$$= \left[\pi(4.0)\ (1.75) + \frac{\pi}{4}\ (4.0)^2\right]\ (.047)\ (.30)$$

$$= 0.486 \text{ lb}$$

Energy required to warm walls from 70°F to 200°F

$$Q = m\ Cp\ \Delta T$$

$$Q = (.486)\ (.30)\ (130)$$

$$Q = 190 \text{ Btu}$$

$$\text{Mass of aluminum can} = \left[\pi\ D\ h + \frac{\pi}{2}\ D^2\right]\ \rho \times t$$

$$= \left[\pi(4.0)\ (1.375) + \frac{\pi}{2}\ (4.0)^2\right]\ .10\ (.030)$$

$$= 0.127 \text{ lb}$$

Energy required to warm aluminum can from -10°F to 180°F

$$Q = m\ Cp\ \Delta T$$

$$Q = (.127)\ (.21)\ (190)$$

$$Q = 5.06 \text{ Btu}$$

Mass of food in 4-inch can

$$\text{Volume of can} = \frac{\pi}{4}\ D^2\ h = \frac{\pi}{4}\ (4.0)^2\ (1.375) = 17.30$$

$$\text{Food mass} = (17.30) \left(50\ \frac{\text{lbs food}}{\text{ft}^3}\right) \frac{1}{1728} = 0.50 \text{ lb}$$

Energy required to warm food from -10°F to 160°F

$$Q = Q_{(-10 \text{ to } 32)} + Q_{\Delta\text{phase}} + Q_{(32 \text{ to } 160)}$$

$$Q = .50\ [70\% \times .501 + 30\% \times .4]\ 42 + .50\ (70\% \times 144) +$$

$$.50\ [70\% \times 1.0 + 30\% \times .4]\ 128$$

$$Q = 9.90 + 50.4 + 52.5 = 112.8 \text{ Btu}$$

Total transient energy required

$$Q_{total} = Q_{walls} + Q_{can} + Q_{food}$$

$$Q_{total} = 190 + 5.06 + 112.8$$

$$Q_{total} = 307.87 \text{ Btu}$$

Assume a steady radiation loss from surface of can

$$Q_{loss} = A \, \varepsilon \left[\sigma T_c^{\,4} - \sigma T_o^{\,4}\right]$$

$$Q_{loss} = (.087)\ (0.5)\ [207.7 - 140.41]$$

$$Q_{loss} = 2.92 \text{ Btu/hr}$$

where

$T_c \approx 130°F$

$T_o \approx 75°F$

$\varepsilon \approx .50$

Heat required to warm 4-inch food can and cavity in 30 minutes

$$Q_{heater} = Q_{total} + Q_{loss}$$

$$Q_{heater} = \frac{307.87}{.50} + 2.92$$

$\underline{Q_{heater} = 608 \text{ Btu/hr}}$ for each 4-inch cavity

Repeating the analysis for the 2.75-inch food can and cavity, find

$\underline{Q'_{heater} = 352 \text{ Btu/hr}}$ for each 2.75-inch cavity

A.7.2 Power Analysis. Determine Max Power required by tray concept, assuming 1.591 lb of food.

Closest to this food compliment would be three 4-inch cans or two 4-inch cans plus two 2.75-inch cans for a combined food mass of 1.50 pounds.

$$Q_{(4\text{-inch cans})} = 3\ (608\ \text{Btu/hr}) = 534\ \text{watts}$$

$$Q_{(2\ +\ 2\ \text{cans})} = 2\ (608) + 2\ (352) = 562\ \text{watts}$$

Thus, maximum theoretical power is 562 watts (per tray)

A.7.3 Weight and Volume Analysis.

Tray weight = 3.98
Electrical hardware = 0.52
Total weight per man = 4.50 pounds

Tray volume $= L \times W \times t$
$= (16 \times 13 \times 4.50)\ \text{in}^3$
$= 0.541\ \text{ft}^3$
Electrical hardware volume $= 0.059\ \text{ft}^3$

Total volume per man $= 0.60\ \text{ft}^3$

REFERENCES

NOTE

The primary sources of data for this handbook were References 1, 2 and 3.

1. "Final Report, Space Station/Base Food System Study, Volume 1, Systems Design Handbook" Fairchild-Hiller Report MS 128V0010, 31 December 1970.

2. "Data Book Space Station/Base Food System Study, Book 1, Element Concept Data Sheets" Fairchild-Hiller Report MS 128W0002, 31 December 1970.

3. "Data Book Space Station/Base Food System Study, Book II, Support Technical Data" Fairchild-Hiller Report MS 128W0002, 31 December 1970.

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